The Dynamic Earth

GEO 101 Laboratory Manual

2025–2026

Edited by Dr. Bo Zhang, Associate Professor
Department of Geological Sciences | University of Alabama

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Chapter 1: Exploring Geology Using the Alabama Museum of Natural History

Have you ever considered how long the Earth has existed? Do you know that geologist measures units of time in thousands, millions, and billions of years? In this lab, you will learn about the geologic time scale and the age of the Earth.

LEARNING OBJECTIVES:

1) To explore the oldest natural history museum in the state.
2) Learn about the geologic history of Alabama and geologic time.
3) Lay the groundwork for this lab class.

INTRODUCTION

Geology is an interdisciplinary science that encompasses all natural processes to obtain a better understanding of the present, past, and future. Geology encompasses erosion, sedimentary processes, water systems, earthquakes, volcanoes, exploring rock at the surface of the Earth and in the subsurface to interpret the Earth's history. These studies are important because humans use the natural resources of water, natural gas, oil, and coal every day. Geologists spend time outside mapping areas, exploring rocks, measuring data in the rocks, and taking rock, sediment, or water samples to bring back to the laboratory for experiments. Some geologists perform chemical analyses in the laboratory, use microscopes to look at samples to determine small scale process, and use computers to model geologic processes from the data collected.

Geology Fields:

Geochemistry- focuses on the distribution of chemical elements in groundwater and Earth materials.

Geophysics- study of the Earth's motions, gravitational field, magnetic field, earthquake-related events to better understand geodynamic processes and improve models of Earth's interior.

Volcanology- study of volcanoes, lava, and related geological, geophysical, and geochemical events.

Structural Geology- study of the three-dimensional distribution of rock, their surfaces and composition to learn about the history, past environments and events that changed or deformed the rocks.

Hydrogeology- study of the quantity, composition, distribution, circulation, and physical properties of surface water and groundwater.

Geological Engineering- uses geology to assure that the geological factors regarding the location, design, construction, operation, and maintenance of engineering works are recognized and accounted for.

Paleontology- study of fossils to trace the evolution of plant and animal life and to decipher the geologic history of the Earth.

Mineralogy- study of minerals to classify minerals and minerals systems according to their composition, genesis and structure.

Sedimentology- study of sediments to determine the origin, and distribution of sedimentary rocks, such as gravel, sand, silt, and mud, and understand the processes involved in sediment accumulation and/or genesis of economically important deposits.

Planetary Geology- geologic study of other planets, moons, and asteroids through the analysis of extra-terrestrial materials (e.g. meteorites), or from data collected from missions using remote sensing.

Igneous and Metamorphic Petrology – study of rocks that come from a melt and rocks that have been changed through intense pressure and temperature.

Geochronology- study of dating rocks and materials to determine the timing of geological events.

Oceanography- study of Earth's oceans and coastal waters to understand coastal process, undersea geology, biological evolution, broad-scale oceanic circulation patterns, and climate change.

Glaciology- study of physical properties and movement of glaciers and ice sheets, sometimes using such information to contribute to contemporary discussions of future climate change.

Geomorphology- study of the origin and evolution of landforms and landscapes created by physical, chemical or biological processes operating at or near the Earth's surface.

BACKGROUND

The Alabama Museum of Natural History (AMNH) is part of the University of Alabama Museums and is in Smith Hall. Opened in 1910, it is the **oldest** natural history museum in Alabama, and one of the oldest natural history museums in the nation. AMNH's mission is to broaden the knowledge of natural sciences and human culture through collections and quality programs of research, instruction, and service. (For more information, see https://almnh.ua.edu/teachers-corner.html).

Time in the present is measured from a starting point and increases until today's date. We acknowledge years, months, days, hours, minutes, and seconds. By contrast, geologists measure time starting from the present and count backwards, the opposite of the way you tell time. Measurements of time are given different names: An eon is the largest increment of time, and it contains 2 or more eras; An era contains millions of years. The increment of time that we primarily explore in this laboratory exercise is a called a geologic period. Other increments of time, such an epoch or age, describe smaller amounts of time, the way you might describe a day or an hour.

The commonly used units of times by geologists include

- Billions of years ago = Ga
- Millions of years ago = Ma
- Thousands of years ago = Ka

Eon	Era	Period		Epoch	Approx. Age (Ma)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	2.4
		Neogene	Tertiary	Pliocene	5.3
				Miocene	23
		Paleogene		Oligocene	34
				Eocene	55.8
				Paleocene	65.5
	Mesozoic	Cretaceous			145.5
		Jurassic			200
		Triassic			251
	Paleozoic	Permian			299
		Carboniferous		Pennsylvanian	318
				Mississippian	359
		Devonian			416
		Silurian			423
		Ordovician			488
		Cambrian			542
Precambrian	Proterozoic				2500
	Archean				4000
	Hadean				4600

Figure 1-1: Simplified version of the Geologic time scale.

EXERCISE

In this lab, you will "tour" The Alabama Museum of Natural History in Smith Hall and answer corresponding questions. All questions can be answered using information in the Museum descriptions. The exhibits in the Museum are Ancient Sea Monsters in Alabama, Rocks, and Minerals from around the world, *Basilosaurus cestodes*, Skulls & Skeletons, and Footprints in Stone.

Name _____ Alabama Museum of Natural History

A. Rocks and Minerals from Around the World

1. For the following rocks and minerals, state a distinguishing characteristic or fact of the rock/mineral. If it is a rock, there is no mineral class. If it is a mineral, write down the mineral class.

Mineral/Rock	**Mineral Class**	**Distinguishing characteristic / fun fact**
Celestite		
Beryl		
Sodalite		
Vesuvianite		
Topaz		
Coal	--------	
Sandstone	--------	
Microcline (Potassium Feldspar)		
Marble	---------	
Halite		
Sylacauga Meteorite ('Hodges')	---------	
Quartz		
Hematite		
Fluorite		
Gold		
Copper		
Sulfur		
Corundum		

2a. What is the definition of a rock?

2b. What rock could you use every day and how? (critical thinking question)

3a. What is the definition of a mineral?

3b. What mineral could you use every day and how? (critical thinking question)

4. What is the state mineral of Alabama? _____

5. What is the most common mineral class found on Earth? _____

6. Different minerals have different shapes – cubes, needles, sheets. Why do you think they are formed this way? (critical thinking question)

B. Paleontology and Geologic Time

The Earth is 4.6 billion years old. Modern time is considered "0 million years ago" while the very beginning of time is considered "4.6 billion years ago." We denote millions of years ago with the unit symbol "Ma" and billions of years ago with "Ga."

1. Figure 1-1 shows a simplified version of the geological time scale. The chart below has the periods. Fill in the chart by finding fossils in the age range listed and then state if the fossil lived on land or in the sea.

Periods	**Name of the fossil**	**When the animals or plants were alive, was it terrestrial (on land) or marine (in the sea)?**
Quaternary: 0-2.4 Ma		
Tertiary: 2.4-65.5 Ma		
Cretaceous: 65.6-145.5 Ma		
Jurassic: 145.5-200 Ma		
Permian: 251-299 Ma		
Pennsylvanian: 299-318 Ma		
Mississippian through Cambrian 318-542 Ma		

2a. Where are Cretaceous rocks found in Alabama?

2b. Are there marine or terrestrial fossils in the rocks?

2c. If there are marine or terrestrial fossils in the rocks, why are those types of fossils found in those rocks?

3. What are the oldest fossils found in Alabama?

4. What Ice Age animals lived in Alabama?

5. What is Alabama's state fossil? Describe when, where, and what environment the animal lived in.

6. What geologic time period interests you the most? What is a dominant species of that time?

7. According to geologic time, what eon, era, period, and epoch are we in today?

8. What makes the Sylacauga meteorite (also called the 'Hodge's meteorite') so extraordinary?

Chapter 2: Discovering Plate Boundaries

The Earth is not made of cheese (neither is the Moon). The Earth is made of rock and has different layers that include a small percentage of partially molten rock. In this exercise, you will explore how the outer layer of the Earth moves around the surface and how scientists know that the plates move.

LEARNING OBJECTIVES:

1) Gain experience working in groups.
2) Gain experience making observations and hypotheses.
3) Understand the evidence for knowing where the plate boundaries are located.
4) Explore the different types of plate boundaries.

MATERIALS: Laminated maps on the wall, plate boundary maps, colored pencils.

THE EXERCISE:

You will be assigned to one of four of the following 'Scientific Specialties', and to one of ten 'Plates or Plate Groupings'.

The Scientific Specialties are:

A. Seismology
B. Volcanology
C. Geography
D. Geochronology

The Plates or Plate Groupings are:

1. North American Plate
2. Pacific Plate
3. African Plate
4. South American Plate
5. Eurasian Plate
6. Cocos/Nazca/Caribbean Plates
7. Australian Plate
8. Antarctic Plate
9. Indian Plate
10. Arabian Plate

Each Scientific Specialty group has a world map showing data relevant to locating plate boundaries and understanding plate boundary processes. Each student has two Plate Boundary maps (p14 & 16). Mark these maps with colored pencils as described below and ***turn them in at the end of the exercise.***

Period 1: Assemble in your Scientific Specialty groups with your group's map.

Task 1. Look at your group's map and talk about what you see. What you look for will vary with data type. For the point data (volcanoes and earthquakes) you are looking for distribution patterns. For surface data (topography and seafloor age) you are looking for where the surface is high and where it is low, where it is old and where it is young. **Work as a group**. Let everyone talk about what they see. After establishing world-wide patterns, look at these boundaries and state what kind of boundaries are between these plates.

Task 2. Now focus your attention on the plate boundaries. Observe your data near the plate boundaries. Is it high or low, symmetric or asymmetric, missing or not missing, varying along the boundary or constant along the boundary? **By yourself**, come up with 5 observations about the patterns of your data. **As a group**, classify the plate boundaries based on the collective observations of your group's data. Restrict yourselves to about 4-5 boundary types. At this point, **do not try to explain the data; just observe!**

Task 3. Assign a colored pencil color to each boundary type in your classification scheme. Color your first Plate Boundary Map to locate your group's boundary types. If the data are asymmetric at a particular boundary type, devise a way of indicating that on your plate boundary map. Each person should mark the boundary types identified by the group on their own map. Each person should write down descriptions of

the group's plate boundary classifications on the back of their map. These maps and descriptions will be turned in at the end of the exercise.

Period 2: Assemble in your Plate groups.
Task 1. Each person should make a brief presentation to the rest of their group about their Scientific Specialty's data and classification scheme. Your group may move to each map in turn while doing this or you may have smaller maps for each group to use.

A 'classification scheme' is a way that you can divide objects into groups based on common characteristics. For example, for 10 different fruit types, you can separate them (or classify them) based on color, shape, taste, or size. The characteristic that you choose to help group the fruits is the "scheme".

Task 2. Compare the classifications of boundary type for your plate based on each type of data. Are there common areas along the boundaries between the different classifications? Can your plate group come up with a new classification scheme that now includes data from all four Scientific Specialties? As above, assign a color to each of your plate boundary types. If a boundary is asymmetric, be sure to devise a way to represent the asymmetry. Mark the boundaries of your plate or plate grouping using your color scheme on your second Plate Boundary Map. Also write a description of the plate boundary classes you have used. The map and description should be turned in at the end of the exercise.

Period 3: TA Summary. Conclude the exercise by summarizing the students' observations and placing them in the context of accepted plate boundary types & plate boundary processes.

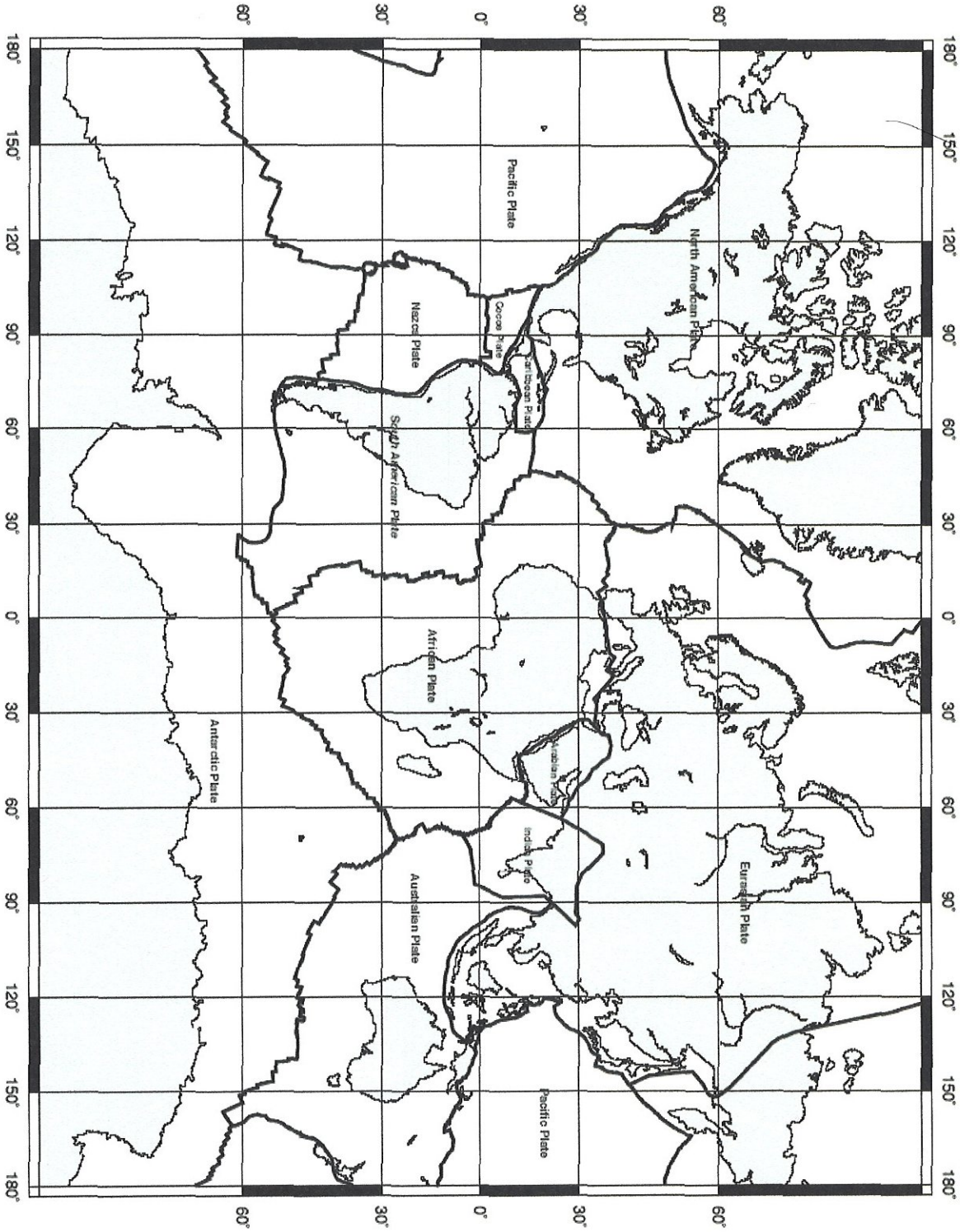
To be turned in by each student after Period 3:

1. Plate Boundary Map classified using data from your assigned scientific specialty. Descriptions of the plate boundary classifications devised by your specialty group should be on the back of the map.
2. Map with your assigned plate's boundaries classified using data from all four scientific specialties. Put descriptions of the plate boundary classifications devised by your plate group on the back of the map.

PLATE BOUNDARY MAP

This map is from Dietmar Mueller, Univ. of Sydney

This map is part of "Discovering Plate Boundaries," a classroom exercise developed by Dale S. Sawyer at Rice University (dale@rice.edu). Additional information about this exercise can be found at http://terra.rice.edu/plateboundary .



Chapter 3: Mineral Identification

What are rocks? You don't know the answer yet, but in this lab, you will learn that rocks are composed of minerals. This lab will introduce you to the concept and process of 'science'. You will learn how to make observations and form hypotheses.

LEARNING OBJECTIVES:

1) Make observations of important minerals.
2) Gain an understanding of the tools used to identify minerals.
3) Gain ability to identify common rock forming minerals using these tools.
4) Learn to write a lab report.

Materials: mineral samples, streak plate, glass, magnet, dilute HCl, nail, penny, gloves

INTRODUCTION

Minerals are naturally occurring, inorganic, crystalline solids with a **definite** chemical composition. Inorganic means that minerals are made from non-living material. Crystalline means that minerals grow in crystal form (eliminates all liquids). A definite chemical composition means that minerals are made from a known combination of elements. The atoms in these elements bond together to form a crystal lattice. This lattice of atoms gives a mineral its crystal form. Although most minerals are chemical compounds, some are elements (e.g., copper, gold, silver). The composition of a mineral can be defined by its chemical formula. For example, the mineral halite (chemical formula = NaCl) is composed of two elements, sodium (Na) and chlorine (Cl) in a 1:1 ratio. However, Olivine has a chemical formula of $(Mg,Fe)_2SiO_4$ and has a range of compositions that are acceptable, where the ratio (Mg+Fe):Si:O is 2:1:4. There could be two Fe atoms or two Mg atoms or one Fe atom and one Mg atom but always one Si and four O atoms.

Mineral Properties We identify minerals by examining their **physical properties**.

Crystal Habit (or Crystal Form): The three dimensional (3D) geometric pattern that a lone crystal of a mineral will have is called the crystal habit, which is governed by the mineral's internal structure. If given enough space, minerals would grow to their characteristic crystal habit (Figure 3-1). However, crystal growth is usually interfered with by the growth of other minerals (competition for space) preventing formation of well-formed crystals. The result is shapeless specimens that developed only a few smooth crystal faces.

Figure 3-1: Three different minerals with three different crystal habits.

Luster: Luster describes the way that light is reflected by the surface of a mineral (Figure 3-2). We will divide luster into two broad groups: 1) The **metallic** luster group has minerals in it that are essentially metals and reflect light. They are also opaque, which means that even when they are cut into very thin pieces, no light passes through them. 2) The **non-metallic** group includes all other lusters (see descriptions of individual lusters in Table 3-1).

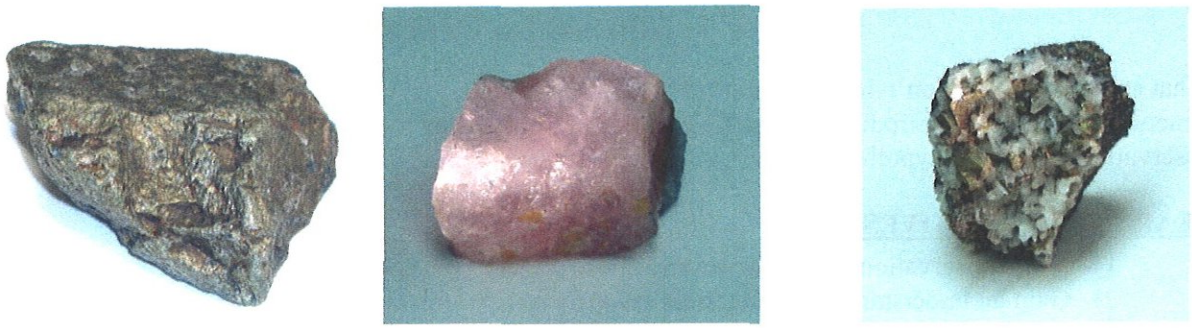


Figure 3-2: Picture on left has a metallic luster. Picture in the middle has a non-metallic luster; it has a pearly luster. Picture on the left is a rock with minerals that have a metallic (gold colored) and non-metallic (white) luster. The minerals have grown together.

Table 3-1: Descriptions of non-metallic lusters.

Luster	Description
Sub-vitreous	Slightly less shiny than glass.
Vitreous	Shines like glass.
Adamantine	Shines brilliantly like a diamond.
Earthy	Very dull, no shine.
Greasy	Surface looks covered in oil or grease.
Pearly	Surface looks like a pearl.
Silky	Surface is slightly textured and shiny like silk.

Color: results from a mineral's chemical composition, impurities that may be present, and flaws or damage in the internal structure. Thus, **color is <u>not</u> a diagnostic way to identify minerals**. For example, quartz can be white, pink, purple or black (Figure 3-3).

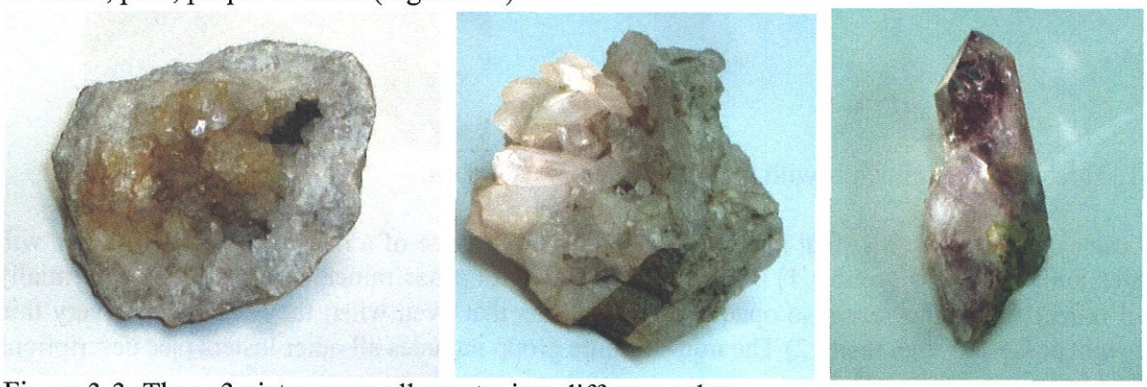


Figure 3-3: These 3 pictures are all quartz, just different colors.

Streak: color of a mineral when powdered. This is determined using a streak plate (Figure 3-4). To powder a mineral, rub it on the streak plate: The color of the powdered residue is the mineral's streak (Figure 3-4). Unlike the observed color of a mineral, the color of streak is a good diagnostic property.

Hardness: resistance to scratching. The hardness of a mineral is controlled by the strength of bonds between atoms and is measured by the ease or difficulty with which it can be scratched. A mineral's hardness is based on a relative scale called 'Mohs hardness scale' (Table 3-2). Different minerals have different values of hardness. For example, a fingernail is 2.25, a copper coin is 3.5, a steel nail is 5-5.5, and glass is 5.5-6. A streak plate (Figure 3-4) has a hardness of 6.5, therefore only minerals with a hardness smaller than this will leave a streak. Any substance that is higher in number is able to scratch a substance with a lower number. Thus, your fingernail (2.25) can scratch a mineral that has a hardness of 1 or 2. A copper coin (3.5) can scratch something that is 1, 2, or 3 but can be scratched by a mineral that is 4 or higher. Therefore, scratching a mineral with several different tools gives you a range for that mineral's hardness. Diamond is one of the hardest minerals, which is why it is used to cut other materials.

Figure 3-4: Observe the streak on the white plate in this picture.

Table 3-2: Mohs Hardness Scale. A fingernail has a hardness of 2.25.

Mohs Hardness Scale

Mineral	Scale Number	Common Objects
Talc	1	
Gypsum	2	Fingernail
Calcite	3	Copper Penny
Fluorite	4	
Apatite	5	Steel Nail
Orthoclase	6	Glass Plate
Quartz	7	Streak Plate
Topaz	8	
Corundum	9	
Diamond	10	

Specific Gravity: the density of the mineral compared to water (1 g/cm^3). Most minerals have a specific gravity in the 2.5-3.5 range. Minerals rich in metals will have higher specific gravities. Specific gravity can be measured precisely or by comparison. You can compare two samples of similar size by holding one in each hand and comparing their "heft".

Fracture: the irregular surface over which a mineral break. The bonds between the atoms are approximately the same in all directions within a mineral (Figure 3-5). There are several different types of fracture. **Conchoidal** fractures are smoothly curved (think of broken glass). An **irregular or uneven** fracture has a rough surface with random breaks. **Splintery** fractures look like pieces of splintered wood.

Figure 3.5: On the left is a general picture of fracture, specifically **conchoidal** fracture. On the right is a close-up view of fracture. Note that when the bonds break, an irregular surface remains.

Cleavage: the tendency of a mineral to break along flat planes, which represents where the bonds between atoms are weaker. Minerals can have up to 6 planes of cleavage. When more than 1 plane of weakness is present, it is important to determine the **angle** between the planes (Figs. 3.7 and 3.8).

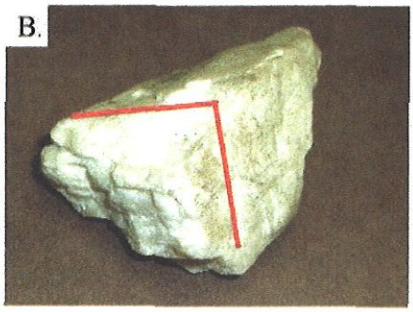
Other Properties: magnetism, taste, reaction to dilute hydrochloric acid (Figure 3-6), double refraction, transparency or opacity, feel (e.g., greasiness). ***Do not taste the minerals.***

Figure 3.6: The mineral in photograph is reacting to hydrochloric acid (HCl), which has been applied to the surface. The formation of bubbles is from a chemical reaction turning the solid mineral into a gas – a process called effervescence.

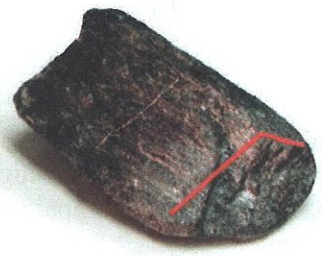
Figure 3.7: Images of minerals with cleavage planes highlighted with red lines. A) mineral has one perfect cleavage; B) mineral with 2 cleavages at 90°; C) mineral with 2 cleavages not at 90°, looking at the obtuse 120° angle; D) same mineral as in C with 2 cleavages not at 90°, looking at the acute 60° angle; E) mineral with 3 cleavages at 90° (cubic cleavage); F) mineral with 3 cleavages not at 90° (rhombic cleavage); G) mineral with 4 cleavages, dashed red lines delineated the top of a pyramid, solid red lines show the 4 cleavages.

A.

B.

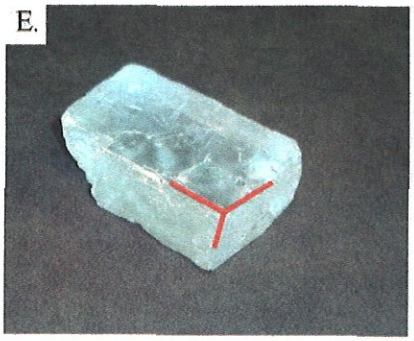


C.

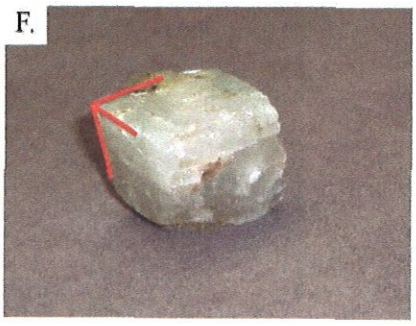


D.

E.



F.



G.

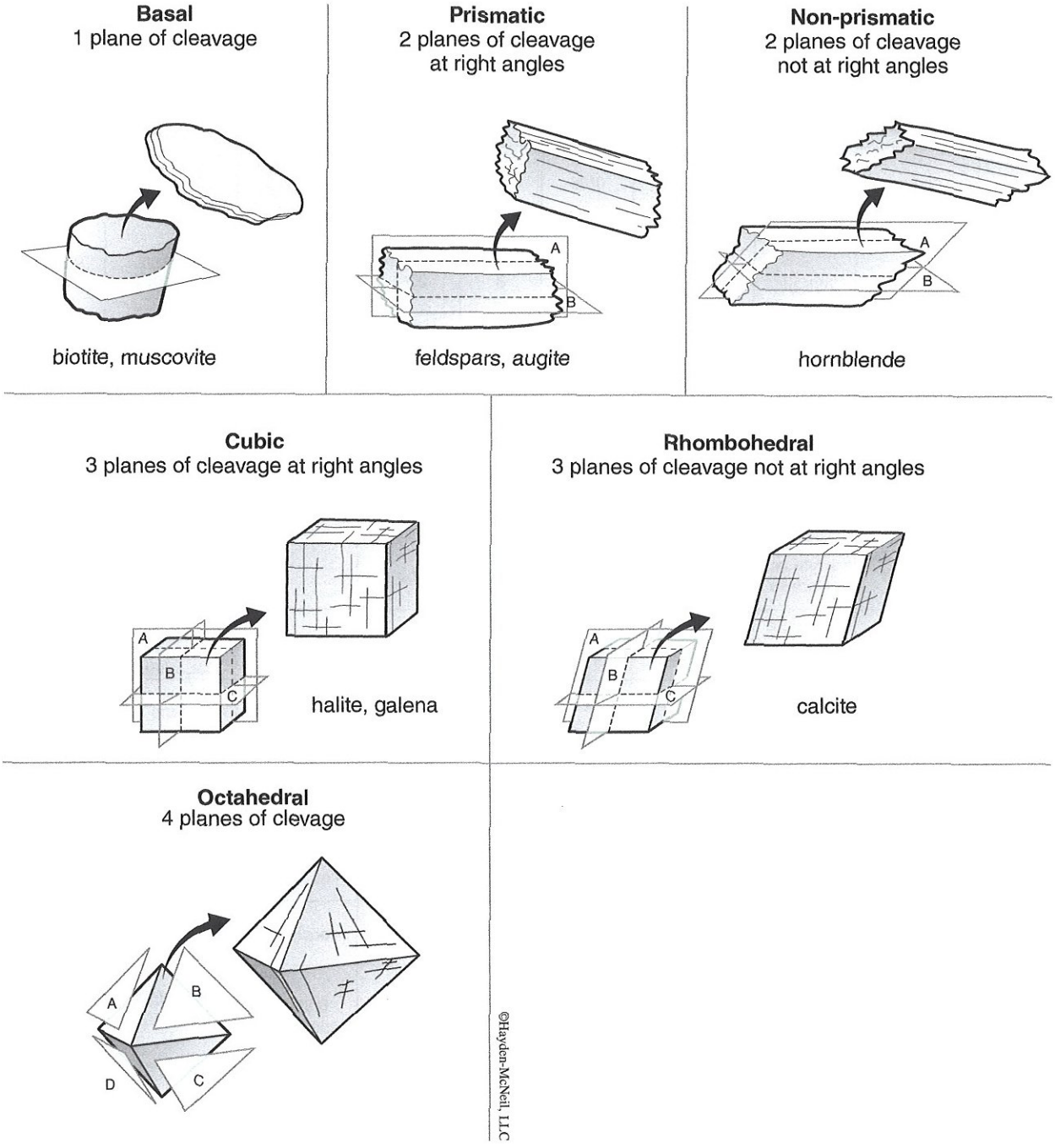


Figure 3-8: 3D schematics showing how cleavage and cleavage directions can be determined from observing a mineral.

Table 3-3 lists some of the aspects of the common minerals. Not all mineral samples will necessarily show these physical properties. For example, all feldspar has cleavage, but the sample you examine may not *show* that cleavage. All minerals have a crystal form (crystal habit) . However, *rarely* do mineral samples show good crystal form. Even museum collections may not contain good examples of a mineral's crystal form.

Table 3-3: Common Lab Minerals and Attributes. **Key properties for each mineral have been underlined.**

Mineral	Crystal Form	Luster	Color	Streak	Hardness	Specific Gravity	Fracture	Cleavage	Other
Amphibole	columns or fibers	vitreous	dark green, black	gray, white	5-6	3-3.47	sub-conchoidal	2 perfect directions at 60° & 120°	
Biotite	plates	vitreous	dark brown, black	gray	2.5-3	2.8-3.4	uneven flat surfaces	1 perfect direction	
Calcite	variable	vitreous	Colorless white, red, gray, green, yellow blue	white	3	2.71	brittle to conchoidal	3 perfect directions (rhombic)	reacts with acid
Feldspar	Elongate prisms	*vitreous*	Pink, white, gray	*white*	6-6.5	2.61-2.76	brittle	2 perfect directions at 90°	
Fluorite	cubes	vitreous	Green or purple	white	4	2.61-2.76	uneven flat surfaces	4 perfect directions	
Graphite	platy or tabular	sub-metallic	Gray	black to dark gray	1.5-2	2.1-2.23		1 perfect direction	pencil "lead"
Gypsum	tabular, or diamond *shaped*	white or colorless	white or colorless	white	2	2.3		1 perfect direction, 2 *poor*	
Halite	cube	transparent or greasy	colorless or white	white	2.5	2.17	brittle	3 perfect directions at 90° (cube)	salty taste
Hematite	tabular crystals	metallic or earthy	gray, brown, reddish	reddish brown	6.5	5.3	conchoidal	none	
Magnetite	octahedron	metallic	gray to black	black	5.5-6	5.1-5.2	sub-conchoidal	none	highly magnetic
Muscovite	plates	vitreous	light brown	white	2.5-3	2.8-3.4	uneven flat surfaces	1 perfect direction	
Olivine	ortho-rhombic	vitreous	green	white	6.5-6	3.2-4.5	conchoidal	poor in 2 directions	
Pyrite	cube	metallic	brass-yellow	gray to green-black	6.5	5	conchoidal	very poor to none	
Pyroxene	columns, granular, massive	vitreous	black, green, brown	green	5-6	3.2-3.6	*brittle to* conchoidal	2 perfect directions at 90°	
Quartz	hexagonal Prisms	vitreous	Colorless white purple gray, brown, yellow	white	7	2.6-2.65	conchoidal	none	
Talc	rhombic or hexagon	pearly or greasy	white	usually white	1	2.7-2.8	uneven flat surfaces	poor in 1 direction	

Steps to Identifying your mineral

1. Determine the luster of your mineral – is it metallic or nonmetallic? (Figure 3-2, Table 3-1)
2. Determine the hardness of your unknown mineral (Table 3-2).
3. Determine the streak of your unknown mineral (Figure 3-4).

4. Examine your specific mineral for any signs of cleavage or fracture (Figs. 3.5, 3.7 & 3.8).
5. Use the Flow Chart (Table 3-4) and Steps 1-4 to help identify your mineral. Table 3-3 also shows diagnostic properties of common minerals.

Table 3-4: Flow Chart for Identifying a Mineral.

Luster	Magnetic	Hardness	Streak	Mineral
Metallic	Strong	> 5.5	Black	Magnetite
	Weak		Brown to Reddish Brown	Hematite
	None		Grey to Greenish Black	Pyrite
		< 5.5	Black to Dark Grey	Graphite

Non-Metallic	Color	Hardness	Cleavage	Streak	Other	Mineral
	Dark-colored	> 5	2 @ 90°	Light Green Colorless	Column-like texture	Pyroxene
			2 @ 60° and 120°	Gray, White Colorless	Fiber-like texture	Amphibole
			Absent	White	Sugary texture	Olivine
		< 5	4 perfect	White		Fluorite
			1 perfect	Grey		Biotite
	Light-colored	> 5	2 @ 90°	White		Feldspar
			Absent	White	Sugary texture	Olivine
				White	Glassy Texture	Quartz
		< 5	1 perfect	White		Muscovite
			1 poor	White	Softest Mineral	Talc
			1 good, 2 poor	White		Gypsum
			3 @ 90° (Cubic)	White	Salty Taste	Halite
			3 not @ 90° (Rhombic)	White		Calcite
			4 perfect	White		Fluorite

FOR NEXT WEEK: Review the minerals that you identified today. **You will have a quiz next class** that will require you to identify eight of the following minerals. Use this chart as a self-study quiz to help you review.

The minerals you will need to know how to identify are:

Quartz	Feldspar	Hematite	Fluorite	Olivine	Muscovite
Biotite	Graphite	Talc	Halite	Gypsum	Magnetite
Calcite	Pyroxene	Hornblende	Pyrite		

Num.	Mineral	color	streak	hardness	cleavage	crystal form	luster	fracture	other

Chapter 4: Igneous Rocks

Do you have a granite countertop in your kitchen? Have you ever used a pumice stone? Do you ever wonder where these materials come from? In this lab, you will learn about granite, pumice, and other igneous rocks.

LEARNING OBJECTIVES:

1) Learn some basic facts about volcanoes;
2) Learn how magmas crystallize;
3) Learn to classify igneous textures and compositions;
4) Learn to identify igneous rocks in hand-sample.

INTRODUCTION:

Igneous rocks form when melted parts of the mantle and Earth's crust solidify into new rocks. Melting of Earth's crust can be caused by a variety of events, ranging from rare asteroid impacts to constant plate tectonic processes to volcanic activity.

Plate Tectonics, Volcanoes, and Plutonism

Plate tectonics is the **driving force** behind many major geological processes on Earth. One of these processes is the **formation of molten rock**. The most familiar type of molten rock is **lava**, which is extruded from volcanoes and cooled onto Earth's surface in layers. Molten rock that cools below the Earth's surface is called **magma**.

The composition of igneous rocks is controlled by the type of plate tectonic environment in which a magma or lava forms. There are 4 main types of compositions for igneous rocks: **felsic**, **intermediate**, **mafic**, and **ultramafic**.

Felsic- high amount of quartz and feldspar, light colored igneous rock (usually pink or white)
Intermediate- "middle" composition between felsic and mafic (gray color)
Mafic- high amount of pyroxene, amphibole, and Ca-rich feldspar (dark-near black color).
Ultramafic- high amount of olivine and pyroxene (very dark, commonly green due to olivine)

These compositions have a direct relationship to the violence of volcanic eruptions:

- Felsic and intermediate lavas are **more explosive** because they have a higher viscosity. This means that the lava does not flow easily, and instead is thick and sticky, like "peanut butter". The higher viscosity is caused by these lavas having a high silica content. They are cooler temperature lavas.
- Mafic and ultramafic lavas are much **less explosive** due to having a lower lava viscosity. This means that they flow easily, the lava is thinner, like "syrup". These lavas contain much less silica. They are also higher temperature lavas.

Volatiles (such as water and CO_2) can also influence volcanic eruptions because they turn into gases, which increase the explosiveness of an eruption. Volatiles are typically found in subduction zone volcanoes due to the presence of hydrous minerals (minerals containing water) in the down-going (subducting) slab/plate. The water released from the subducting plate helps create the molten material that feeds subduction zone volcanoes, because it lowers the melting point of the surrounding material.

Figure 4-1 shows the relationship between tectonics, composition, and explosiveness.

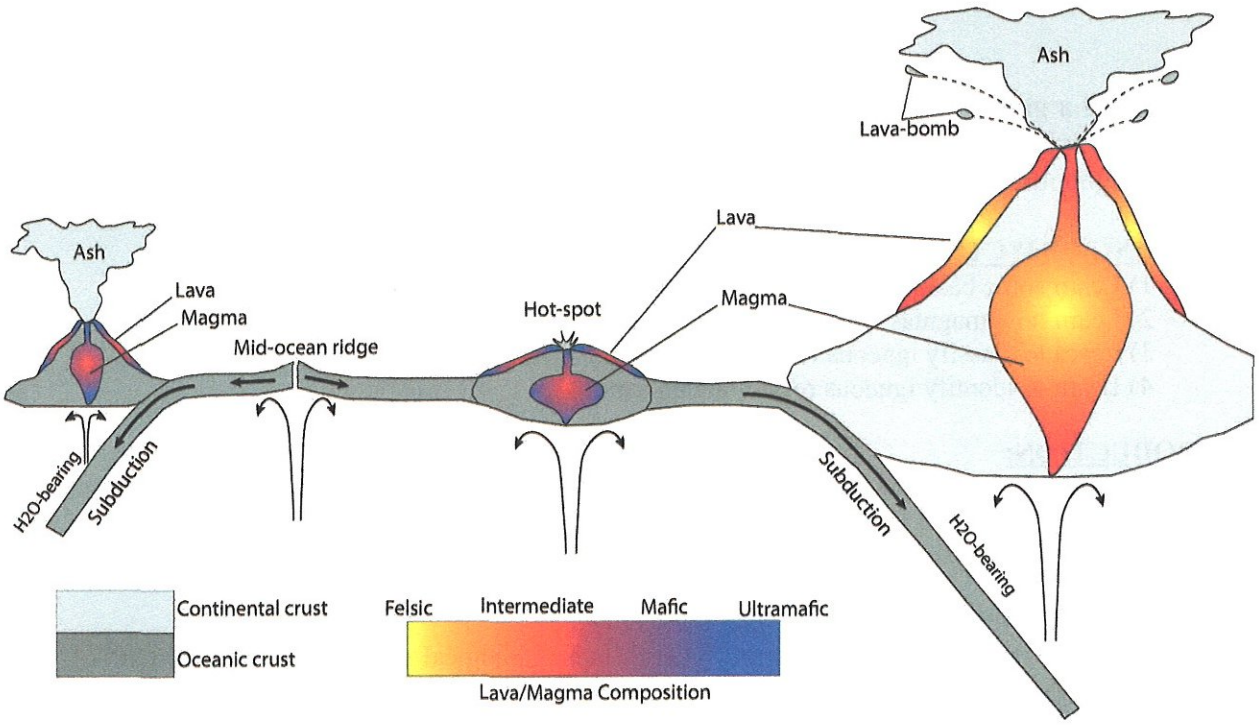


Figure 4-1. A schematic (not to scale) cartoon showing the general relationship between tectonics, composition, and explosiveness on the Earth. The colored scale bar shows different compositions of lava/magma forming in different places, due to the geologic process taking place.

Bowen's Reaction Series:

Looking at the schematic cartoon in Figure 4-1, you might wonder why those different igneous compositions form in different locations.

The answer lies with **Bowen's reaction series** (Figure 4-2).

Bowen's reaction series defines the order of crystallization of minerals present in a magma if a magma chamber were allowed to cool down without interruption. Bowen's reaction series can best be explained by visualizing a plume of source material from Earth's mantle, which is ultramafic in composition. Because we know ultramafic rocks contain a high proportion of olivine, we know that the crystallization temperature for this new rock is high (~1400°C). Following the initial crystallization of olivine, pyroxene and then amphibole will crystallize, in that order. Figure 4-2 shows Bowen's reaction series and the order of crystallization. If that plume of ultramafic material pools below a layer of oceanic crust (low silica content), it will melt the oceanic crust and produce mafic magma. Alternatively, if it pools at the base of continental crust (high silica content) especially with the presence of water (such as the subduction zone at the right-hand side of Figure 4-1), it will melt the continental crust and produce intermediate to felsic magma. The minerals in intermediate and felsic magmas are listed in Bowen's reaction series (Figure 4-2).

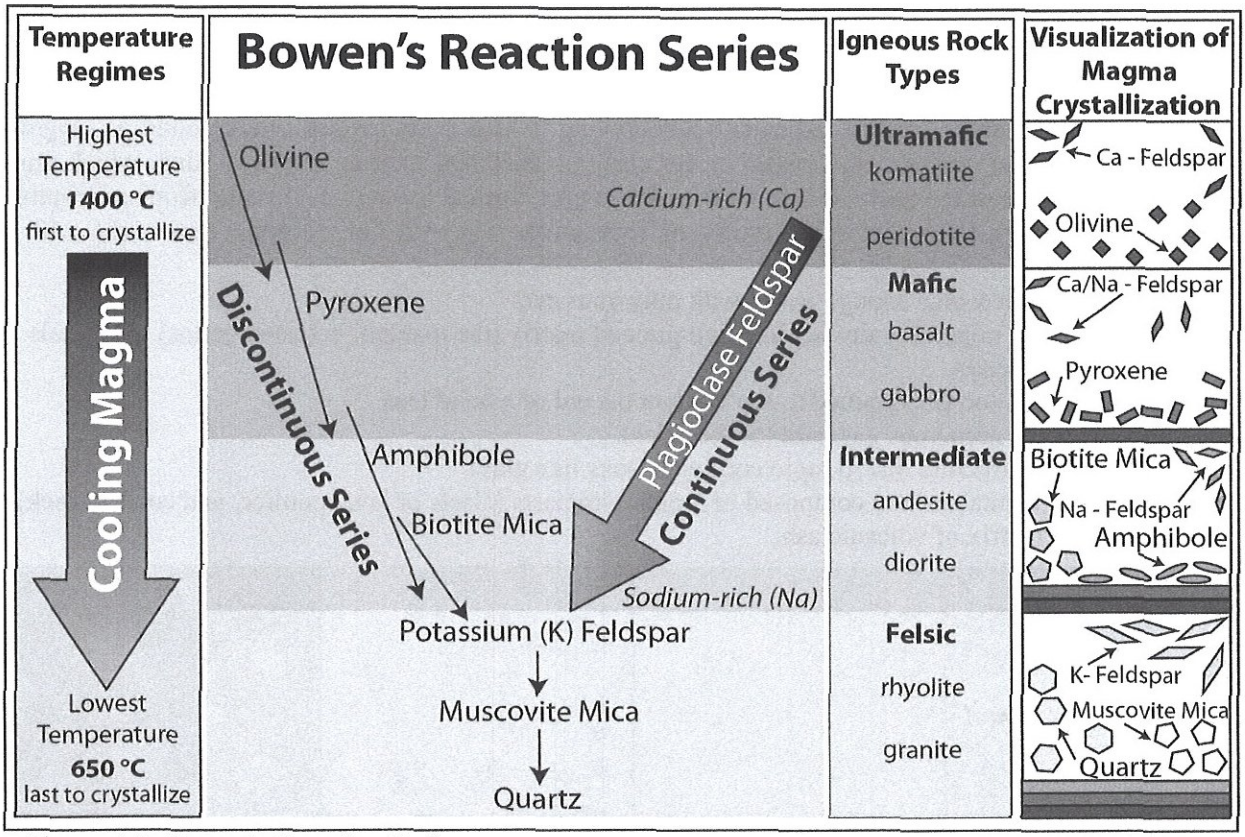


Figure 4-2: Bowen's Reaction Series

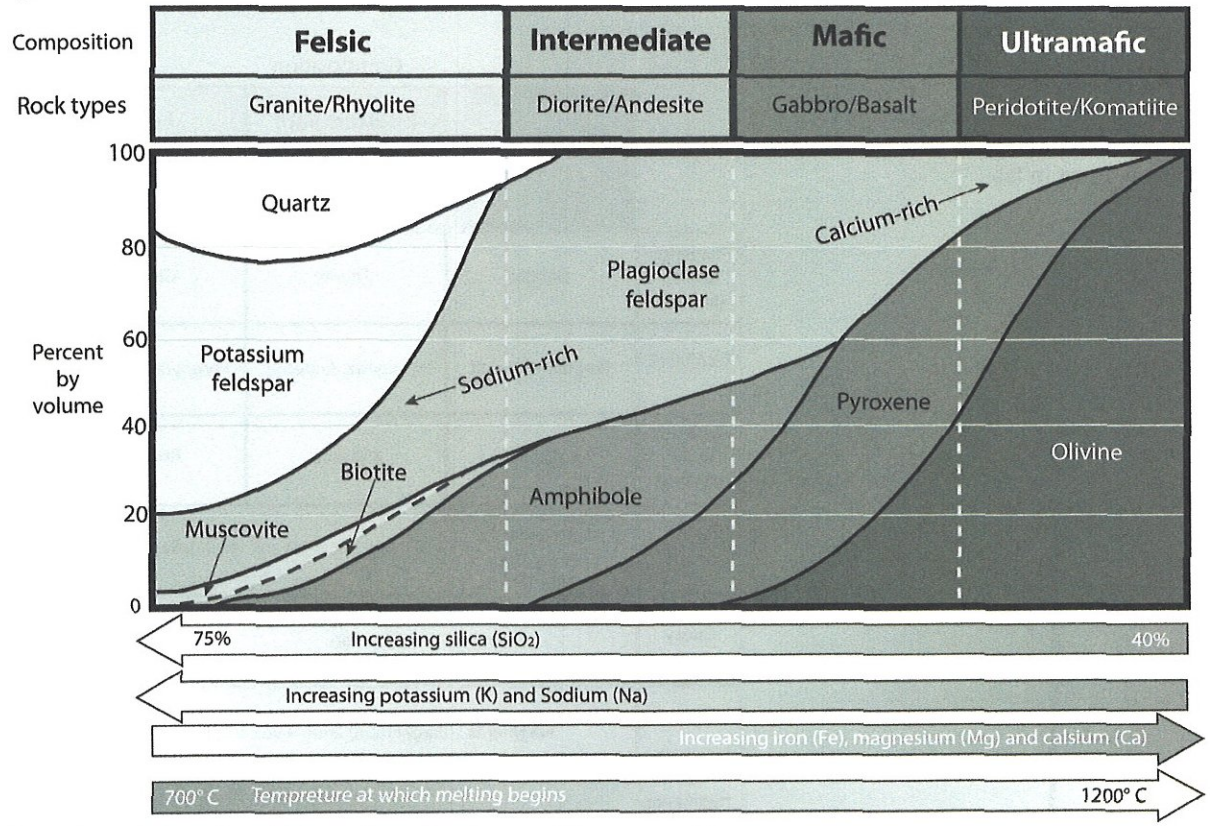


Figure 4-3: Minerals within each rock of a specific composition.

Igneous Rock Textures

Igneous rocks often show patterns or 'textures' that relate to the minerals present in the rock. The texture of an igneous rock can tell us a lot about how quickly it cooled and if it was cooled from magma, lava or ash. Textures with larger crystals indicated **slow** cooling, which must happen underground as magma. Textures with smaller crystals, no crystals or vesicles (gas bubbles) indicate **rapid** cooling, which must happen at the surface of the Earth as lava flow. Ash can only form at the surface, usually from an erupting volcano, and will glue together other pieces of rock when it is still hot, forming new rocks with a 'pyroclastic' texture.

Phaneritic: Minerals coarse enough to see with only your eye.

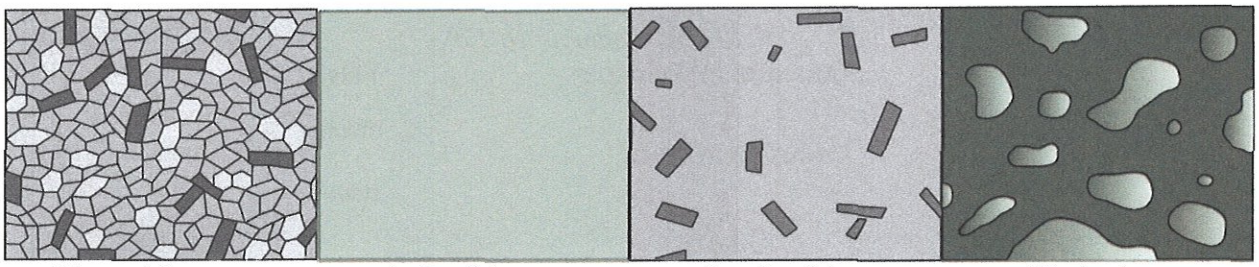
Porphyritic: *Larger mineral grains set in a fine-grained matrix (the material between grains)* of crystals and/or glass.

Aphanitic: Minerals too fine grained to see without the aid of a hand lens.

Vesicular: Contains numerous gas bubbles (vesicles).

Glassy: No crystal structure due to rapid cooling. Looks like glass.

Pyroclastic: Fragmental texture composed of larger pyroclasts (clasts of lava, pumice, and country rock) in a matrix of volcanic ash.

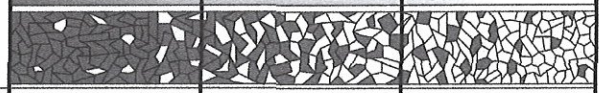


Phaneritic Aphanitic Porphyritic Vesicular

Table 4-1. Igneous rock identification chart. Use texture and composition to identify the rock name of the samples you are given in lab.

Intrusive or Plutonic

Extrusive or Volcanic

Texture	Composition: Mafic	Intermediate	Felsic
			
Phaneritic (coarse grained)	Gabbro	Diorite	Granite
Porphyritic	Porphyritic Basalt	Porphyritic Andesite	Porphyritic Rhyolite
Aphanitic (fine grained)	Basalt	Andesite	Rhyolite
Vesicular	Vesicular Basalt (Fewer and larger bubbles) Scoria (a lot more smaller bubbles)	Pumice (the most and the smallest bubbles)	
Glassy	Obsidian		
Pyroclastic or fragmental	Fragments > (larger than) 2mm = Volcanic Breccia		
	Fragments < (smaller than) 2mm = Volcanic Tuff		

Chapter 5: Sedimentary Rocks

What kind of rocks do we see around Tuscaloosa? How can a rock give clues about where it came from? The Grand Canyon in Arizona is mostly composed of sedimentary rocks, but why is it there and how did it form?

LEARNING OBJECTIVES:

1) Explore the differences between detrital, biochemical, and chemical sedimentary rocks.
2) Learn to identify sedimentary rocks in hand-sample and thin-section.
3) Learn how clues in rocks can lead to and understanding of the environment of deposition.

INTRODUCTION

Weathering & Erosion → Transportation → Deposition → Lithification

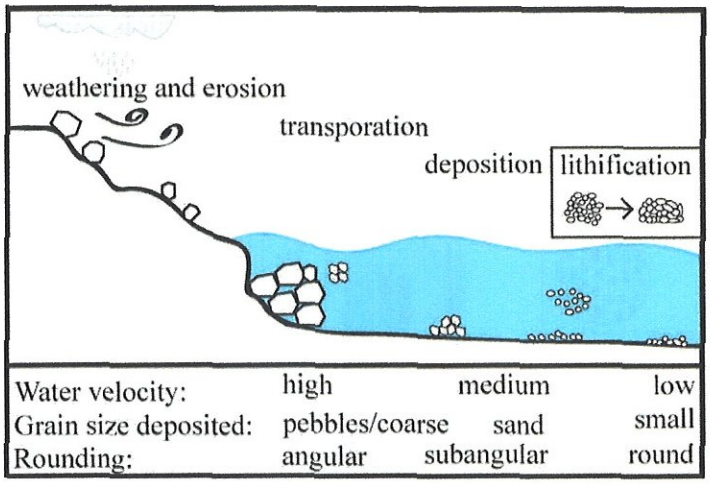


Figure 5-1: A schematic showing the different stages of creating a sedimentary rock.

Weathering & Erosion

When rocks are exposed at the surface of the Earth, **weathering** begins. **Erosion** processes move the weathered material by water, wind, ice, or gravity. If the weathered rock is not removed, a soil begins to form. There are two main types of weathering processes – physical (or 'mechanical') and chemical.

- **Physical weathering** breaks down the rocks into smaller fragments of rock. In regions, such as the desert, where water is lacking but there are large changes in temperature (either daily or seasonally), physical weathering is dominant.
- **Chemical weathering** breaks down the internal structure of the minerals in the rock, and the minerals are dismantled ion by ion. **Water** is the most important chemical weathering agent, and transports the ions and molecules removed from the minerals. In regions, such as Alabama, which has an abundance of rainwater as well as high temperatures, chemical weathering is dominant.

Transportation

The bits of sediment worn or dissolved from the rock are transported by water or wind. A river transports the weathered materials, or sediment, as either solid particles or dissolved chemicals to a different location. During transport, fragments of rock are **rounded** and **sorted**. This process will also incorporate animal and plant parts with the wind or water. The more a sediment is transported, the more rounded it will be, and the more 'sorted' – where all grains in the sediment are about the same size (see p.44-45).

Deposition

When the velocity of the water decreases, such as when a stream flows into a lake or river, solid sediment, animal and plant material (the sediment load) is dropped out of the water column and deposited at the bottom of the water body. Sediment transported as chemicals in solution is precipitated into new minerals that are then deposited on the bottom of a water body. Sediment settles out or precipitates out of the water (transforms a dissolved substance into a solid) to the bottom of the lake or ocean. This sediment is usually deposited horizontally in parallel layers called strata or bedding; this is called **Steno's Law of Original Horizontality.** Because rocks are deposited in layers, the layers stack up over time. Thus, the **Principle of Superposition** states that in sedimentary rock layers, the oldest rock unit is on the bottom and the youngest rock unit is on the top.

Lithification

To make a new sedimentary rock, the sediment must be 'lithified', meaning that it is changed from soft sediments into solid rock. Lithification occurs after the fragments have been buried, compacted, and cemented. The processes of lithification, compaction, and cementation are low pressure and low temperature changes, termed **diagenesis**. During compaction, water and air is squeezed out of the sediment during the process of forming a rock. The sediment particles are stuck together by naturally occurring **cement** formed by minerals that grow between the sediment particles. Common cements include calcite, quartz and iron. After the fragments become stuck together via these diagenetic processes, a sedimentary rock is formed.

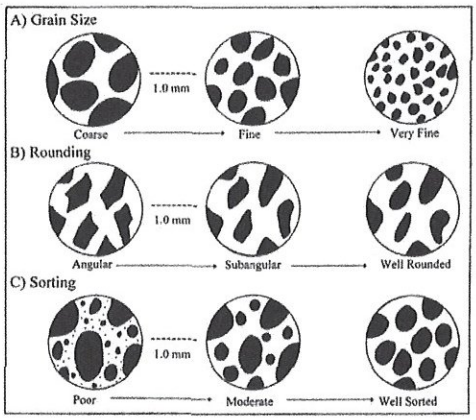


Figure 5-2: Simplified chart illustrating differences in grain size, rounding, and sorting.

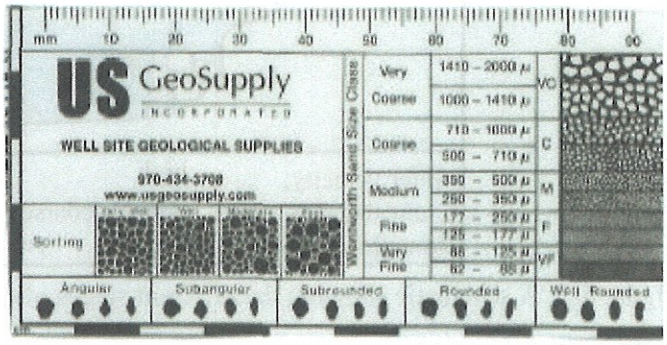


Figure 5-3: Grain Size Card. On the right side, a rock is held up to the chart to determine the grain size in a sandstone. The degree of rounding of grains is determined along the bottom. Just above that, the degree of sorting can be determined.

BACKGROUND

Types of Sedimentary Rocks (see Table 5-1)

Clastic: made from sediment that formed through mechanical weathering of rocks, and transported as solid particles. Clastic rocks include shale, sandstone, conglomerate and breccia. Determination of the rock name is based on the grain size (Figure 5-2). Figure 5-3 is a grain size card used to help name a rock. Figure 5-4 is a picture of a clastic rock.

Chemical: composed mainly of crystals or grains that precipitate out of water in lakes, the ocean, or groundwater. Chemical rocks include evaporites (rock salt and rock gypsum), dolostone, travertine and chert. Figure 5-5 is a picture of a chemical rock.

Biochemical: these rocks contain a large amount of biological material in the form of fossils or limestone. Biochemical rocks include coquina, chalk, and limestone.

Organic: forms from organic debris and organic-rich sediment, includes peat and various types of coal.

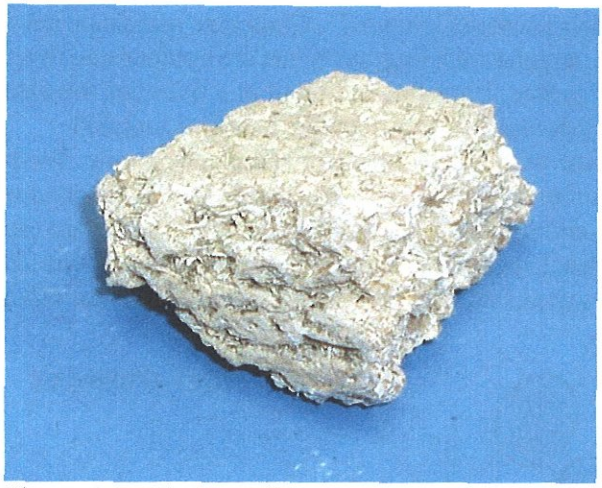


Figure 5-4: Clastic sedimentary rock. Individual grains are apparent.

Figure 5-5: Chemical sedimentary rock. Individual grains are NOT visible, interlocking crystals grew together during precipitation.

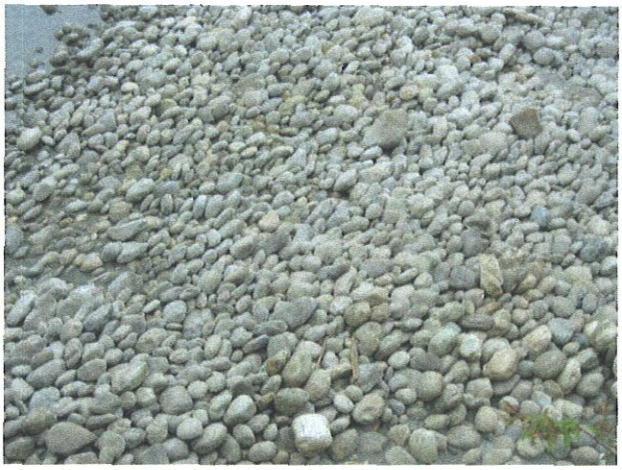


Figure 5-6: Well sorted and rounded cobbles in a riverbed in central Nepal. Notice that the cobbles are nearly all the same size, thus well sorted. Cobbles are rounded and have very few sharp edges. North is up the page in this picture. Flow direction

Figure 5-7: (upper right) Poorly sorted and subangular conglomerate/breccia. The size of the fragments varies from twice the size of the hammer head to smaller than the hammer head. The shape of the fragments varies from rounded (see fragment by hammer head) to angular (see white rock in upper right-hand corner). Photo of the Dumri Formation, western Nepal.

Sorting and Rounding in Detrital Rocks

The degree of **rounding** of sedimentary particles also provides information about sediment transport. The degree of rounding refers to the amount of abrasion a sediment fragment has endured. Grains that have been transported a long distance have had ample time to become abraded by contact with other grains and thus, have smooth faces. The further a grain is transported, the fewer sharp edges it retains, and the more rounded the grain appears. Well-rounded grains have usually been transported a long distance from their source (Figure 5-6). Conversely, highly angular grains have sharp corners or edges, and may have been deposited

very close to where they were weathered from a rock, their source (Figure 5-7). Grain size and shape are a rough measure for the distance of transport. For example, angular rock fragments that are boulder size (over 8 feet in diameter) have not traveled very far from their source. Very fine sediment in a river has traveled far from its source. Fragments are described as angular, sub-angular, sub-rounded, and well rounded.
Sorting refers to the degree of uniformity of particle size within a sediment or sedimentary rock. Well-sorted sediment is dominated by particles very similar in size (Figure 5-6). Poorly sorted sediment contains a range of particle sizes (Figure 5-7). As with grain size and rounding, the relative sorting of sediment can be used as a proxy regarding the transport history of detrital sedimentary rocks. A rock that is well sorted has usually traveled far from its source; whereas poorly sorted sediment has not had time to become sorted and indicates it has not traveled far from its source.

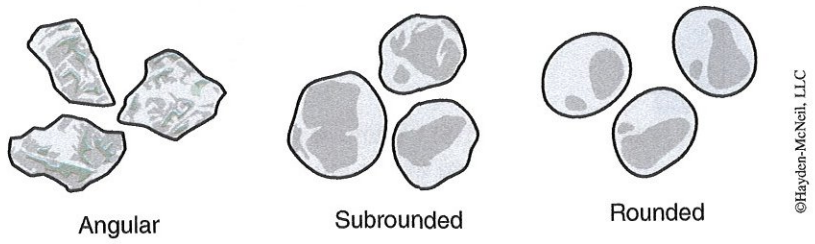


Figure 5-8: Degree of rounding

Table 5-1: Classification of sedimentary rocks.

Clastic Sedimentary Rocks

Rock	Description	
Shale	very small grains, composed of mud of grain size <1/16 mm, may easily split into layers (fissile) or may be break into blocks, commonly dark gray	Increasing Grain Size ↓
Sandstone	fine to coarse grained, composed of sand with grain size from 1/16-2 mm, maybe mainly composed of quartz, feldspar, &/or rock fragments	
Conglomerate	composed of rounded pebbles and gravel with grain sizes larger than 2mm	
Breccia	composed of angular fragments of rock with grain sizes larger than 2mm	

Chemical, Biochemical, and Organic Sedimentary Rocks

Rock	Description
Limestone (microcrystalline)	biochemical, fine- to coarse-grained, crystalline, effervesces in dilute hydrochloric acid, composed of calcite, white, gray or black
Chert	chemical, amorphous, composed of massive silica (quartz), conchoidal fracture, hardness = 7
Rock Gypsum	chemical, fine- to coarse-grained, massive or granular gypsum, hardness = 2, white, gray or pastel
Rock Salt	chemical, fine- to coarse-grained, crystalline or massive halite, hardness = 2.5, commonly white or light orange
Coal	organic, fine-grained organic matter, made from plant fragments, dark brown or black, low density
Coquina	biochemical limestone, visible shell fragments loosely cemented, effervesces in hydrochloric acid
Limestone (fossiliferous)	biochemical limestone, visible shell and shell fragments cemented with calcite cement, effervesces in hydrochloric acid
Chalk	biochemical limestone, composed of microscopic marine shells, white and soft, effervesces in hydrochloric acid

Environments of Deposition

If a sediment-making process is operating (e.g., weathering, erosion), and if the sediment can be deposited in a river, lake, or ocean, **sedimentary rocks can form**. Areas where sediment is being deposited are called 'depositional environments' (Figure 5-9). Clues in each rock give an idea as to what type of environment a rock was deposited. For example, if you see something in a rock that can only form in water, then the environment in which that rock formed was in the water! To determine the environment of deposition, one must make observations about the rock and then interpret those observations.

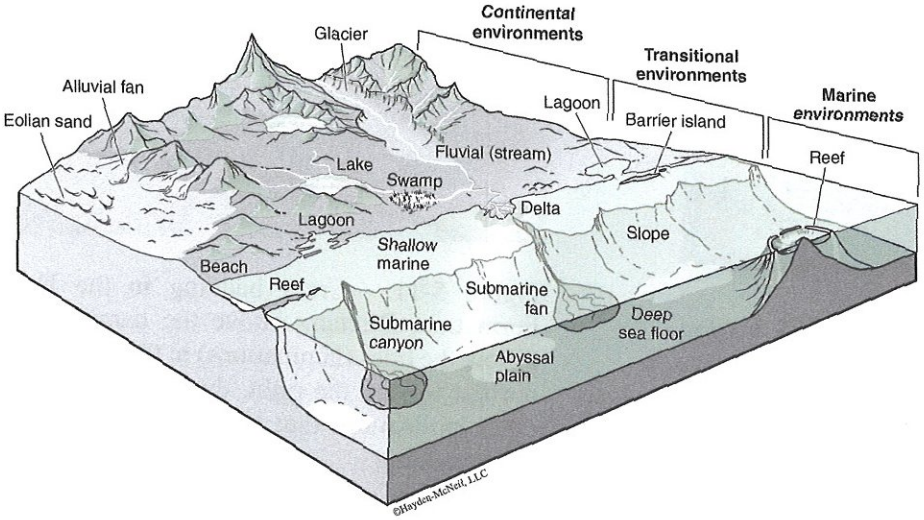


Figure 5-9: Environments of Deposition where sediment can be stored to eventually become a rock after it is lithified.

Here are a few examples: An *evaporite* forms when water evaporates leaving behind a salt in mineral form (e.g., halite, gypsum). These form in the shallow-most marine settings. A *terrestrial or continental* environment occurs in places other than the ocean (e.g., swamps, rivers, lakes). Cross bedding is caused by water flowing in a direction and occurs in this environment. *Shallow Marine* environments typically have fossils that are in large or whole pieces with sedimentary structures like ripple marks (see below). *Deep Marine* environments of deposition do not contain whole pieces of shells or entire animals because it is not the easiest for habitation. Therefore, when bones and shells travel due to moving water, they will become broken and disoriented. If a calcium carbonate is in the water column and becomes over saturated, it will start to come out of the solution and become a deep marine limestone, which might not contain any fossils.

Sedimentary Structures and Paleocurrents

Sediment is deposited in packages of horizontal layers called **strata**. Strata are composed of much smaller-scaled layers called **beds**. This fine layering is known as **lamination** and can be either parallel to the beds (parallel lamination) or inclined at an angle to the bedding (cross bedding). All kinds of laminations, as well as other features generated by currents during deposition of sediment, are called **sedimentary structures**. Ripples form when currents move sediment along a riverbed, in tidal pools or the sea floor (Figure 5-10, also see ripple marks on the rock in front of Smith Hall). Cross bedding (Figure 5-11) results when sediments migrating along a riverbed or sea floor are piled up into ripples and other bedforms by currents. The inclined lamination results from sediment avalanching down the steeper side of the ripple. To preserve sedimentary structures, they must be turned into a rock soon after they occur, or other sedimentary processes, such as erosion, will erase them. Geologists can use these sedimentary structures to determine which way a stream/river was flowing, to determine the 'paleocurrent'. Two examples of paleocurrents are the ripples in Figure 5-10 and the cross bedding in Figure 5-11. One way to determine paleocurrent is the imbrication of the rocks. Figure 5-12 shows imbricated clasts (or rocks). In this photograph, the clasts are

leaning to the right. The power of the water that deposited the rock flipped the rocks so that they all lean in the same direction. This shows that the water flowed from left to right, as illustrated in Figure 5-13.

Figure 5-10: Ripple marks in the Fagfog Formation, central Nepal. Ripple marks indicate the presence of water. Thus, this rock formed in either a stream or river. Umbrella

Figure 5-11: Cross bedding in the Daling Formation, Bhutan. Above the hammer head, follow the lines (laminations) in the rock that are not flat toward the right, they are truncated by other laminations that are also not flat. This is cross bedding.

Figure 5-12: Clasts (rocks) in a debris flow from Alaska. The clasts were deposited when a huge thunderstorm caused sediment to be washed down a canyon and subsequently deposited.

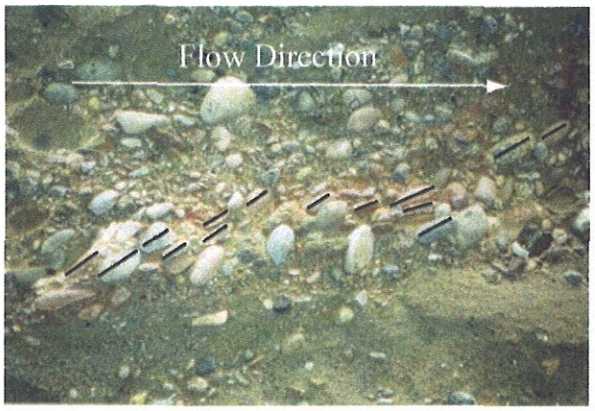


Figure 5-13: The same picture but annotated with the black lines outlining leaning clasts. The rocks lean toward the right so that is the way that the water flowed.

Chapter 6: Metamorphic Rocks and the Rock Cycle

Do you want to know whether a marble countertop is real? Do you wonder how an igneous or metamorphic rock becomes a sedimentary rock, or how metamorphic and igneous rocks are related? In this lab, you will explore metamorphic rocks and the rock cycle.

LEARNING OBJECTIVES:

1) Observe how pressure & temperature influence the mineralogy & texture of metamorphic rocks.
2) Learn to identify metamorphic rocks in a hand sample.
3) Learn basic concepts of rock cycle.

PROCESSES OF METAMORPHISM:

Recrystallization: As temperature and pressure increase, the bonds that hold atoms together begin to break and reform (remember, minerals are composed of atoms arranged in a lattice structure). If the rock is composed primarily of one mineral such as quartz (SiO_2), then the bonds will reform into larger crystals of quartz. Thus, recrystallization leads to a change in the texture of a rock, not to a change in composition.
New mineral growth: An increase in temperature and pressure on a rock composed of many minerals will cause bonds holding the atoms to break and then reform bonds that will form totally different, new minerals. This process can completely alter the mineralogy of the original parent rock. Textural changes can also occur. For example, temperature increases can lead to larger crystal sizes. Some minerals may grow larger than others. These large grains are called porphyroblasts.
Metasomatism: A rock's composition can be altered by removing elements from the rock and/or introducing new elements into the rock. This is called metasomatism and it is generally caused by circulation of hot, water-rich fluids, called hydrothermal fluids. As hydrothermal fluids move through the body of rock, metasomatism can occur as hydrothermal fluids are extruded from a body of magma into the surrounding rock, or as groundwater circulates near magma or deep enough to get hot and then moves into overlying rock. Economic deposits of metals such as native copper, gold and silver can result from metasomatism.

TYPES OF METAMORPHISM:

Contact metamorphism: When intrusive igneous rocks intrude into cooler rocks, the heat from the intrusion causes the surrounding rock to heat up, which induces recrystallization and new mineral growth. In addition, fluids released or heated by the intruding magma may lead to metasomatism. The zone of rock around the intruding magma affected by metamorphism is called the aureole. New minerals will form by replacing pre-existing minerals in the aureole.
Regional metamorphism: At convergent plate boundaries, large regions of the lithosphere are metamorphosed due to heating as rocks are buried and experience pressure (stress) of the collision. In the core of the collision, the greatest metamorphism occurs where igneous rocks intrude beneath the arc volcanoes. Further away from the intrusions, lower temperature, but high pressure, metamorphism occurs.
Hydrothermal metamorphism: At mid-ocean ridges, large volumes of water are circulated through fractures in hot oceanic lithosphere. This circulation pattern removes some elements and deposits new elements, altering the composition of the rock.

TYPES OF METAMORPHIC ROCKS:

Metamorphic rocks are classified based on the texture, which is the size, shape, and arrangement of the minerals in the rock. The rocks are categorized into two main types: foliated and non-foliated textures.
Foliated texture: Because metamorphic rocks are subjected to intense directed stress or pressures, a crude layering is produced called foliation. Foliation is produced when minerals become aligned perpendicular to the directed stress (Figure 6-1). As the intensity of foliation increases, the mineral grain size may increase via recrystallization into larger, more visible crystals. Thus, as metamorphism intensifies from low-grade

to high-grade metamorphism, there is a general increase in foliation and a corresponding increase in grain size (Figure 6-2). Eventually, the increasing pressure and temperature mobilize ions, which then migrate into distinctive bands of light and dark minerals called gneissic layering, and may increase to the point where there is a percentage of partial melt, called migmatite.

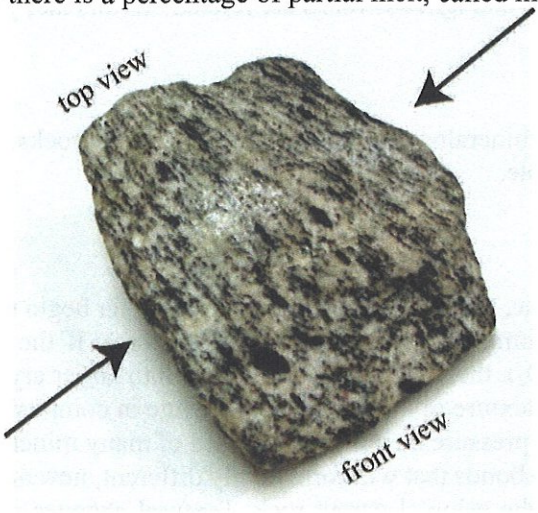


Figure 6-1: Directed stress (pressure) caused by tectonic forces or the force of the overlying rock cause the minerals to align.

Rocks at the surface of the Earth are not subjected to the pressures and temperatures that rocks experience at depth. From the Earth's surface to ~15 km depth, **rocks are brittle** when subjected to stress. If these rocks are squeezed, they break (and cause earthquakes). Below ~15 km, **rocks are ductile** when subjected to stress. The pressure and temperatures are high enough to heat up the rock and allow the minerals to rearrange themselves, producing rocks similar to those shown in Figure 6-1.

Metamorphic rocks are changed through an increase in temperature, pressure and/or fluids. The original rock, before undergoing metamorphism, is called the parent rock. In the sequence of foliated rocks explained below, the parent rock is shale, the most common sedimentary rock. Shale will change to slate; slate will change to phyllite; phyllite will change to schist; schist will change to gneiss; and if melting begins to occur, gneiss will change to migmatite (see Figure 6-2 for a view of the textures in foliated metamorphic rocks and Figure 6-8 for a chart of foliated rocks). Many different parent rocks [not just shale] can be transformed into phyllite, schist, and gneiss by progressive metamorphism.

Slate: Slate is derived from shale, most of the time, but it can be derived from basalt or another type of fine-grained rock. Shale is mostly composed of clay minerals and then minerals are replaced by mica crystals during metamorphism. As these processes occur, the rock forms a foliation called slaty cleavage that forms as mica grows and rotates into alignment perpendicular to the direction of stress. Slate splits easily along these planes and is utilized as chalk boards or roof shingles (Figure 6-3).

Phyllite: As metamorphism increases, slate is transformed into phyllite. The mica crystals grow larger and align producing a more defined foliation. The foliation has a distinct wavy appearance and is called phyllitic structure. Slate and phyllite contain mineral grains too small to be seen individually without magnification, except for porphoblasts in phyllite.

Schist: *As* metamorphism increases, phyllite is transformed into schist. The mica crystals grow larger and reflect light producing a shiny luster. Schist contains mineral grains that are large enough to be seen with the unaided eye. The type of foliation is called schistosity.

Gneiss: At high grade of metamorphism, schist transforms into gneiss. Other parent rocks are possible such as granite or diorite. The intense pressures and temperatures allow atoms to migrate in the rock and form mineral bands where all the dark minerals align (amphibole and biotite) and all the light minerals align (quartz and feldspar). This foliation is called gneissic foliation.

***Migmatite*:** Each mineral begins to melt at a different temperature. In Bowen's Reaction Series, quartz and feldspar melt at lower temperatures than amphibole or biotite mica. Thus, as the temperature increases, the quartz and feldspar begin to melt to produce light colored leucosomes. The darker minerals form a rim around the leucosomes and are called melanosomes (Figure 6-4). This process of melting the light-colored minerals is called partial melting. If complete melting occurs, once solidified, the rock will be an igneous rock.

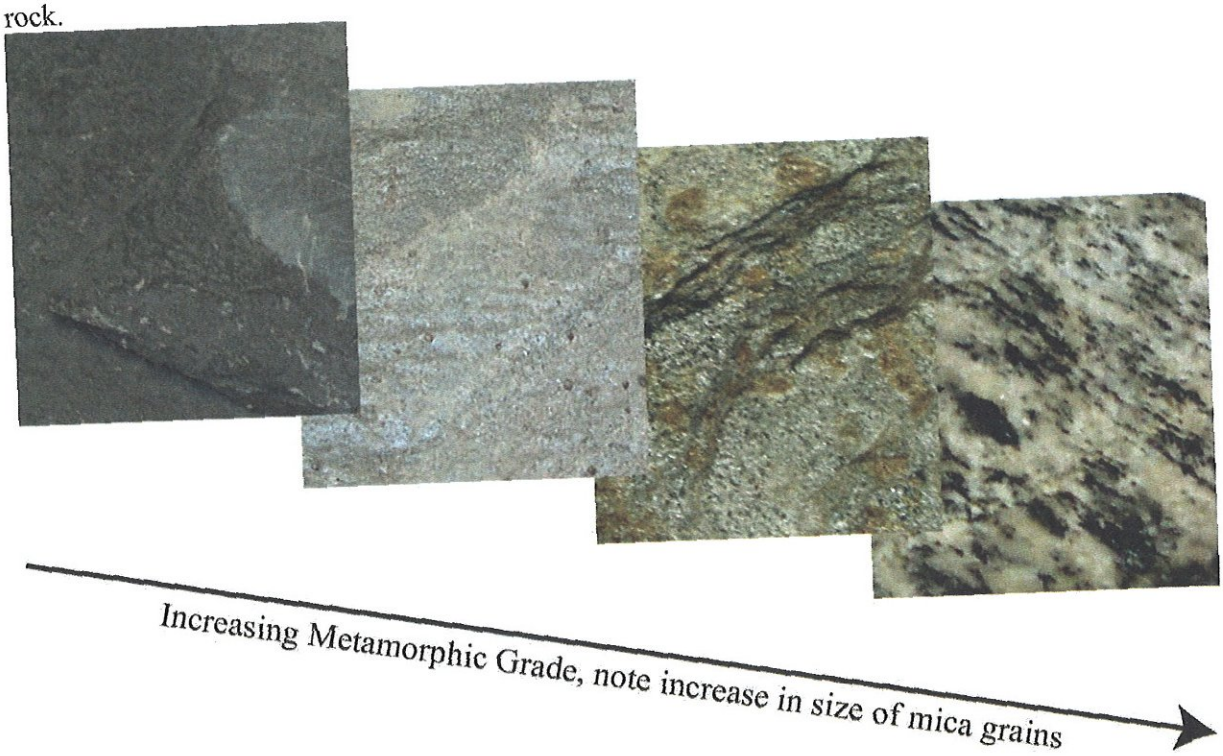


Figure 6-2: Schematic diagram showing the textures in foliated metamorphic rocks. Towards the right, the mica grains get larger and the sheen (shininess) increases.

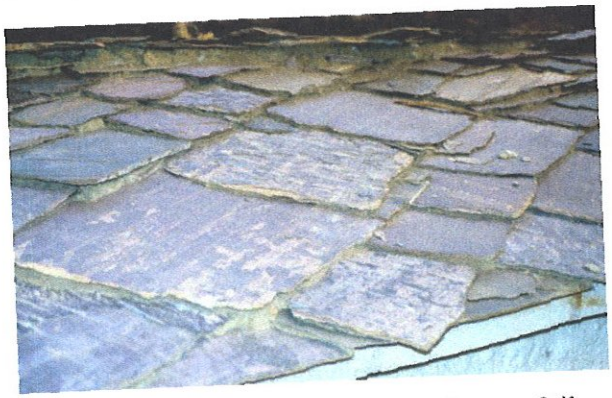


Figure 6-3: Photo of slate being used as roof tiles on a village hut, western Nepal

Figure 6-4: Picture of a migmatitic rock. On the front face, there is a leucosome and surrounding the white pod there are black melanosomes. This rock has partially melted.

Nonfoliated texture: These rocks do not contain a foliation because there was no directed stress to align the minerals. They are formed as temperatures and pressure increase and the bonds in the atoms are broken and reformed to form larger crystals (recrystallization) (Figure 6-5).

Quartzite: When sandstone is metamorphosed, the resulting rock is quartzite. The quartz grains will fuse together forming a crystalline appearance. Because there are different kinds of sandstone depending on the composition, quartzite can also be different colors.

Marble: When limestone is metamorphosed, marble is formed. The calcite crystals in the limestone recrystallize to form marble. Marble looks very similar to quartzite; they both can be pure white. To distinguish between the two, use a drop of dilute hydrochloric acid on the rock. If it effervesces, it is marble. Marble can be an array of colors depending on the composition of the parent rock.

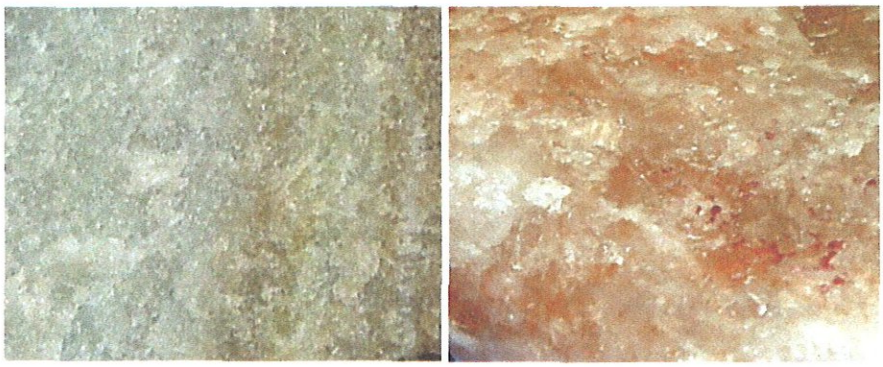


Figure 6-5: Nonfoliated texture. Note how the grains are interlocking like puzzle pieces.

Porphyroblastic texture: Phyllite and schist often contain some larger minerals, porphyroblasts, set in the matrix of the rock. Minerals such as garnet, kyanite, and pyrite are common as porphyroblasts (Figures 6-6 and 6-7). These larger minerals are set in a matrix of smaller sized minerals and is called a porphyroblastic texture. When naming the rock, the porphyroblasts are used as modifiers in front of the rock name (e.g., pyritic phyllite or garnet mica schist).

Figure 6-6: Garnet porphyroblasts in gneiss

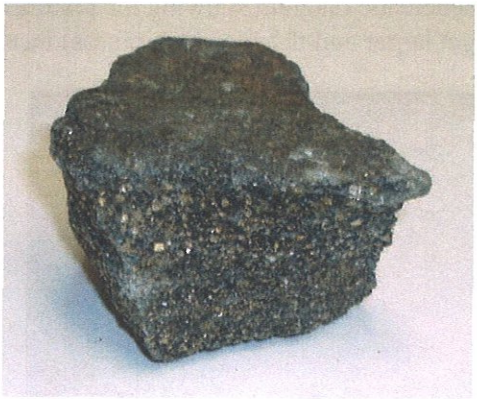


Figure 6-7: Pyrite porphyroblasts in phyllite

Rock Identification:

When identifying metamorphic rocks, here are the questions to ask (Use Figure 6-8).

1. Is the rock sample foliated or non-foliated? If non-foliated, there are only two choices.
2. If it is foliated, what degree of metamorphism has occurred? This can be determined by looking at the grain size of the rock. A name is given to the rock based on the degree of metamorphism.

Foliated Metamorphic Rocks

Rock	Description	Metamorphic Grade
Slate	very fine grained or no grains visible, dense, slatey cleavage, splits into thin plates, commonly dark gray	low-grade
Phyllite	*fine grained, phyllitic cleavage, wavy foliation surfaces,* with microscopic mica flakes which gives a satin sheen	low-medium grade
Schist	medium grained with increasing amounts of mica, schistosity (aligned elongated or platy crystals), crystalline texture, breaks along scaly foliated surfaces	medium grade
Gneiss	coarse grained, gneissic banding (minerals segregated into alternating black and white layers), minerals visible	high grade
Migmatite	coarse grained with flow bands of light rock (leucosomes) surrounded by darker grained rock (melosomes) light rock indicates partial melt	highest grade with a degree of partial melting

Increase in grain size ↓

Nonfoliated Metamorphic Rocks

Rock	Description
Quartzite	fine to coarse grained, composed mainly of fused quartz grains, extremely dense, grains will not rub off like the parent rock sandstone, usually light colored
Marble	fine to coarse grained, microcrystalline (resembling a sugar cube) to a coarse crystallinetexture, recrstallized calcite, calcite effervesces in dilute HCl, usually light colored

No metamorphic grade

Figure 6-8: Classification of Metamorphic Rocks based on texture.

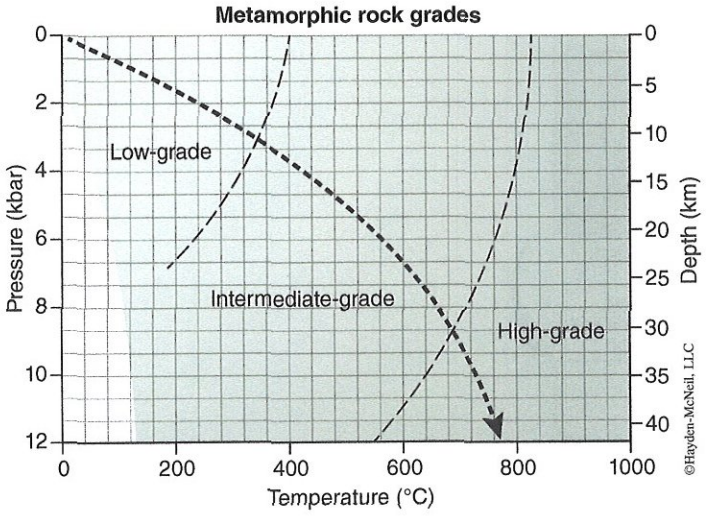


Figure 6-9 shows the corresponding pressures, temperatures, and depth for the different metamorphic grade

THE ROCK CYCLE:

James Hutton (1727-1797), an 18th century farmer and founder of modern geoscience, authored the concept of the rock cycle, which depicts the relationships between igneous, sedimentary, and metamorphic rocks. The upper part of the earth (lithosphere and asthenosphere) is constantly being transformed from one rock type to another. Rocks are created, changed, and broken down *(see Figure 6-10).*

Melted rock solidifies, or crystallizes, to form igneous rocks. Intrusive (plutonic) rocks crystallize at depth from magma. Extrusive (volcanic) rocks crystallize after the lava reached the Earth's surface. As the intrusive igneous rocks solidify at depth, heat and water from the magma can alter the host rock into which the magma intruded, a process called contact metamorphism.

Metamorphic rocks form when a parent rock, or a protolith, is subjected to changes in pressure, temperature or chemistry (such as the addition of water). Regional metamorphism occurs at collisional boundaries, which are areas that undergo very weak metamorphism to very intense metamorphism. If these metamorphic rocks are partially melted, the resulting crystallized rock will be an igneous rock.

Rocks at the surface of the Earth are exposed to ice, wind and water and begin to break down (weather) into smaller grains. These grains are transported in streams and are deposited either by precipitating out of solution or by decreasing the velocity of the stream. Once deposited, these grains become sediments that can then be turned into rock through the lithification process. To become a rock, these sediments need to be buried, then compacted, and cemented together (see chapter 5). If these rocks get buried deep enough, they turn into metamorphic rocks or melt to create igneous rocks. The rock making process can be interrupted at any point if the rocks are brought to the surface and then weathered and turned into sedimentary rocks. Thus, igneous rocks can be metamorphosed to form metamorphic rocks, or uplifted and brought to the surface of the earth and turned into sedimentary rocks or re-melted to form more igneous rocks. Sedimentary rocks can form from the erosion and weathering of igneous, metamorphic or other sedimentary rocks. And, if any rock is changed through increasing the temperature, pressure, or adding fluids, then a metamorphic rock is formed. This interplay and interchanging between rock types is called the rock cycle (Figure 6-10).

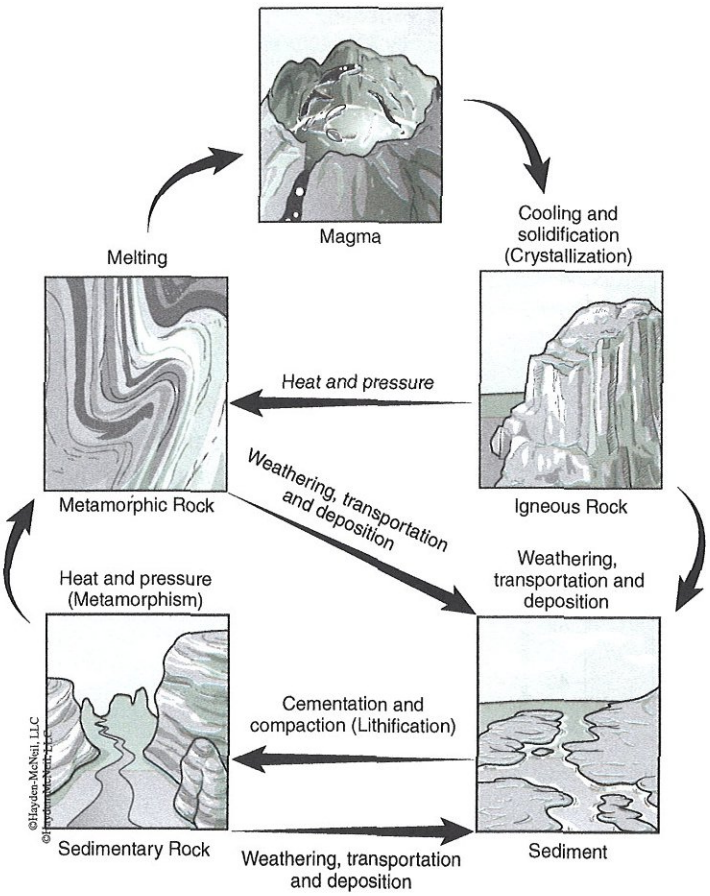


Figure 6-10. The Rock Cycle.

The classification of rocks is based on two criteria, texture and composition. Texture is the size and shape of mineral grains and how these sizes and shapes relate to each other. Each of the three rock types has distinct textures (see separate chapters for more information).

***Igneous Rocks*:** Textures: Phaneritic, Aphanitic, Porphyritic, Glassy, Vesicular, Pyroclastic
***Metamorphic Rocks*:** Textures: Foliated vs. Non-foliated
***Sedimentary Rocks*:** Textures: Clastic vs. Chemical (Biochemical and Organic)

Chapter 7: Fluvial Systems

In this lab, we will learn about river (fluvial) systems. The University of Alabama is built on rock that originated as a river system. Look on campus for evidence of this ancient system.

LEARNING OBJECTIVES:

1) Make detailed and quantitative observations (= collect data) of streams from aerial photos and topographic maps.
2) Classify stream types based on their physical properties and infer the hazards associated with each type.

MATERIALS:

Pencil, eraser, laboratory worksheet, three topographic map/aerial photograph sets (Sets A through C), ruler, calculator, string.

INTRODUCTION:

In this lab, we will explore three different types of rivers and compare their characteristics to determine which river would cause the most damage to nearby communities during a flood.

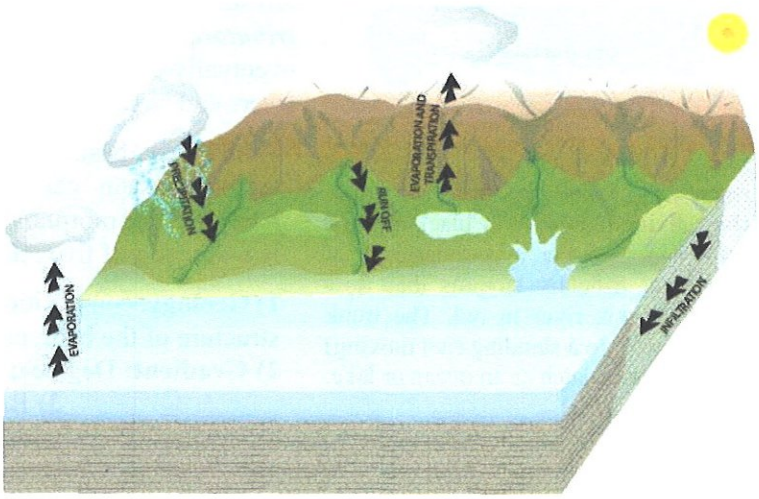


Figure 7-1: All of Earth's free liquid water is constantly in migration through the hydrologic cycle. Major elements of this cycle include surface water in oceans and lakes, surface water flowing in rivers and streams, water falling as precipitation (both as solid and liquid phases), and water vapor traveling as a gas through the atmosphere due to evaporation.

River systems are important for their role as transportation routes, habitats for wildlife, and recreational activities. Rivers are also very sensitive to changes in the ***hydrologic cycle*** (Figure 7-1). Water begins its journey through the hydrologic cycle as precipitation falling from the sky (rain). Some water will infiltrate the ground and become ***groundwater***, while some will flow over the ground as surface water or runoff, forming rivers, lakes, and oceans. In some areas, groundwater leaks from the ground and either forms a spring or seeps into a river channel; in this case, the groundwater seepage is referred to as ***base flow***. Excessive precipitation can cause a river to ***flood***, sometimes with disastrous consequences. In fact, floods cause more damage to human property in the U.S. than any other natural hazard. If a river channel always contains water throughout the year due to water influx from precipitation and base flow, it is termed a perennial stream. It is marked on a topographic map as a solid blue line. If, throughout a year, there is not enough water input and the river channel dries out, then it is called an ***intermittent stream***, which is represented on topographic maps as a blue dotted and dashed line.

Elements of a Fluvial System:

All the different physical aspects of a river combine to form a ***fluvial system***. When looking at the landscapes of the Earth's surface, much of what you see is the result of ***fluvial processes*** (all the processes associated with flowing water). At the largest scale, the ***drainage basin*** is the area that contains streams and rivers that all flow into one trunk channel (Figure 7-2). The boundary that separates one drainage basin from another is called a ***divide***. The ***continental divide*** separates drainage basins that empty out on opposite

sides of a continent. The continental divide of the U.S. falls along the crest of the Rocky Mountains (Figure 7-3). If you were to empty a glass of water on the continental divide, *in theory* the water that falls to the west of the will travel downhill in a fluvial system that transport water to the Pacific Ocean. Water that falls to the east of the divide will travel downhill through a fluvial system that empties into the Gulf of Mexico.

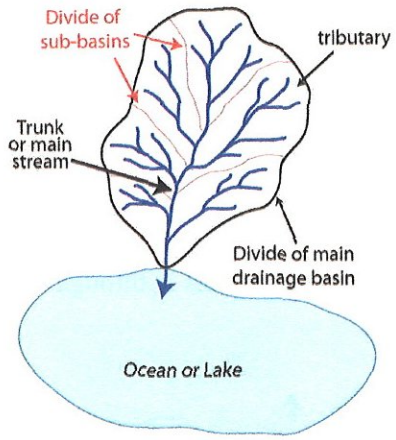


Figure 7-2. A schematic diagram of a river basin, showing the main trunk river divide boundary in black and the sub-basin divide boundaries of individual tributary streams that flow into the trunk river in red. The trunk river flows into a standing (not moving) body of water, such as an ocean or lake.

Drainage Patterns:

Even the largest rivers, when traced to their origin, begin flowing as a trickle of water across the Earth's surface. The origination area of a river is called its ***headwaters***. Sometimes, the headwater region is where water flows over the ground as ***sheet flow***, rather than being absorbed by the ground. In other instances, the headwater area is where a groundwater spring reaches the surface. All surface water flows downhill, and small trickles merge to form ***tributaries*** to streams, which merge as tributaries to rivers, which eventually empty into a lake or ocean. Altogether, the connected rivers and streams form a ***drainage system.***

A drainage basin and the fluvial (river) channels within the drainage basin can exhibit a wide range of morphologies (shapes). The morphology of a drainage basin or a fluvial channel is a function of five main factors:

1) Geology: composition and distribution of bedrock material and structure of the bedrock (faults, folds, etc.)
2) Gradient: Degree of slope of surface
3) Base Level: elevation of standing water in a major body of water, such as a lake, sea, or ocean, into which the fluvial system drains
4) Discharge: Volume of water that passes through a channel over a given period.
5) Sediment Load: Volume of sediment, including sediment carried in suspension as *suspended load,* as well as sediment carried along the bed as *bedload.*

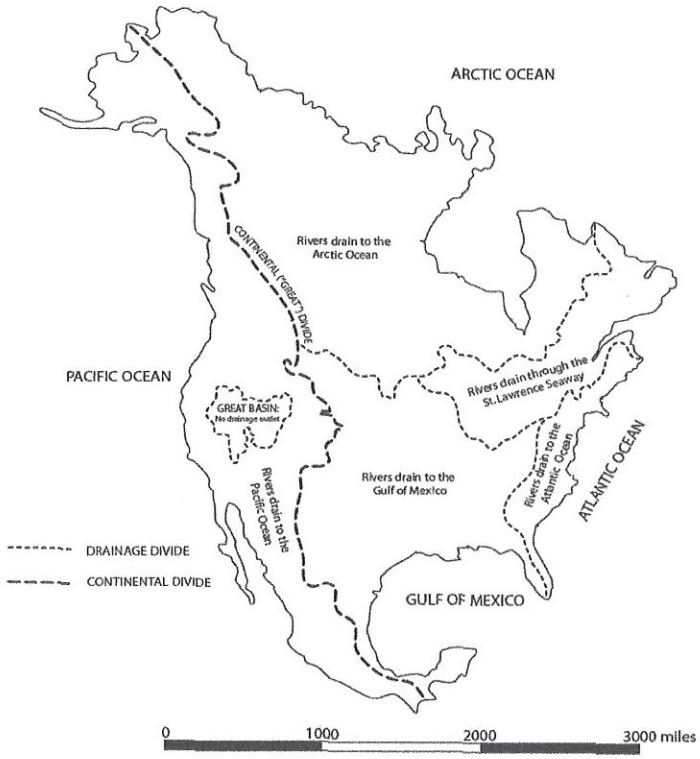


Figure 7-3. The heavy dashed line in the west is the Continental Divide of North America, which separates river basins that drain to the Arctic and Atlantic oceans and the Gulf of Mexico from the river basins that drain to the Pacific Ocean. The Great Basin is surrounded by a divide and is an example of a hydrologically closed or internally drained basin. In the Appalachian Mountains, the dashed line represents the divide that separates water that goes into the Atlantic Ocean from water that drains into the Gulf of Mexico.

Drainage systems draining areas with different bedrock geology will form 6 major patterns of river drainage in map view (Figure 7-4):

1) Dendritic: resembles a branching tree. Branch-like tributaries feed the main or trunk river, common in areas where fluvial systems erode flat-lying layers of rock, or areas of homogeneous crystalline rock (such as igneous rocks) or sediment.

2) Parallel: Channel orientation dominantly in one direction, common for fluvial systems on moderate to steep slopes, or in areas of parallel elongate landforms.

3) Trellis: resembles a vine growing on a trellis. The main trunk channel is long and intersected at right angles by tributaries, commonly where fluvial systems erode tilted, resistant, and non-resistant rock layers and form a series of parallel ridges that separate long valleys. Tributaries flow through these valleys and at some locations intersect the main or trunk channel, cutting across the ridges.

4) Rectangular: channels exhibit 90° bends. This pattern often develops where fluvial systems erode rocks that are fractured or faulted in two main orientations at right angles to one another.

5) Radial: channels flow outward from a central area, resembling the spokes of a wheel, with water flowing away from the hub and out toward the edges of the wheel. This pattern is common where fluvial systems erode an upwarped, dome-shaped area, such as a volcano. Channels that flow inward toward a central area are called **centripetal** drainage. This pattern is formed not by one fluvial system but by several small fluvial systems and so does not count as a drainage pattern of a singular fluvial system *per se*. Centripetal patterns are common in areas where fluvial systems transport water into a bowl-shaped depression, often resulting in the formation of a lake or a playa (a dry lakebed). A special radial pattern is the **annular** drainage pattern, which is a set of incomplete concentric rings of streams connected by short radial channels. This pattern is common where fluvial systems erode structural domes and folds that contain layers of resistant and non-resistant rock.

6) Contorted or Deranged: totally random channel geometry with no recognizable pattern.

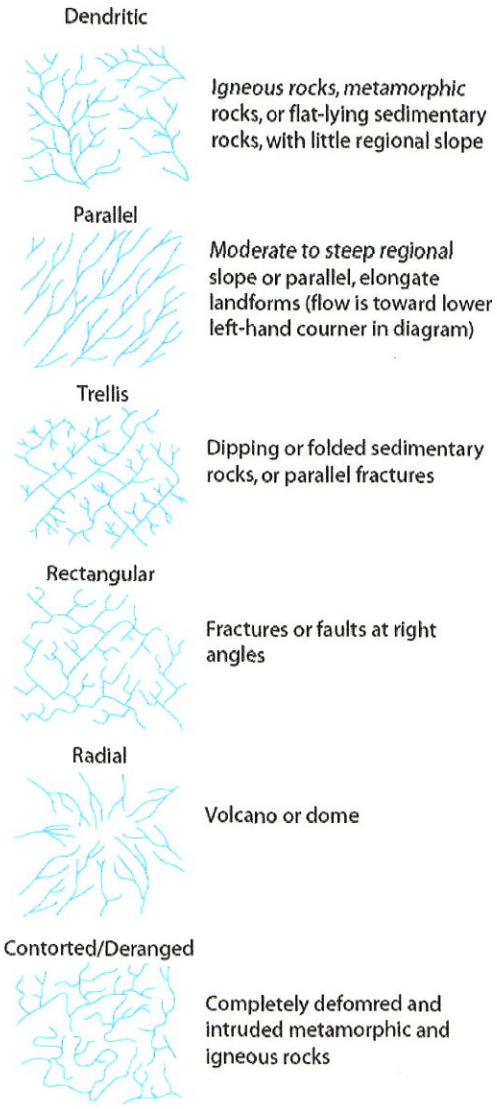

Dendritic
Igneous rocks, metamorphic rocks, or flat-lying sedimentary rocks, with little regional slope
Parallel
Moderate to steep regional slope or parallel, elongate landforms (flow is toward lower left-hand courner in diagram)
Trellis
Dipping or folded sedimentary rocks, or parallel fractures
Rectangular
Fractures or faults at right angles
Radial
Volcano or dome
Contorted/Deranged
Completely defomred and intruded metamorphic and igneous rocks

Figure 7-4. Examples of the different drainage patterns. Each pattern results from different topographic features that are caused by the geology of the bedrock in the area.

River Channels and Floodplains:

Fluvial channels are categorized based on their morphology in ***map view***. Channels are flanked on either side by areas of accumulated alluvium (fluvial sedimentary deposits) known as ***floodplains***. Mostly, deposition occurs here during periods of high water when the river is in flood stage. Large floods that occur rarely will cover the entire floodplain and deposit material across a wide area. In map view, floodplains are typically determined by the extent of vegetation (green coverage on a topographic map) extending away from the riverbanks as well as topographic features, such as limitations due to elevation changes. Small

floods, which are more frequent, will deposit sediment only in the areas immediately adjacent to the river channel, along the riverbanks. Deposits that form along the riverbanks build up to form natural ***levees***.

The morphology of the channel and geometry of the floodplain is controlled by the five main factors mentioned above (See Figure 7-5; geology, gradient, base level, discharge, and sediment load). Where the gradient is low and discharge and sediment load are high, meandering river channel patterns tend to develop (Figure 7-6). In a meandering river channel, erosion occurs on the outer edge of a meander bend, which is called a cutbank. On the inside of a meander bend, deposition occurs to form a ***point bar***. As deposition occurs on one side and erosion occurs on the other, the channel tends to migrate laterally or "meander" over time. In some cases, during a flood, a new channel may form a shortcut across the point bar, rather than flowing around the entire meander bend. This is known as a ***meander cut-off***. The old river channel is now abandoned on the floodplain, and water remains trapped in the abandoned channel segment. This abandoned channel forms crescent-shaped ***oxbow lakes*** (Figure 7-7).

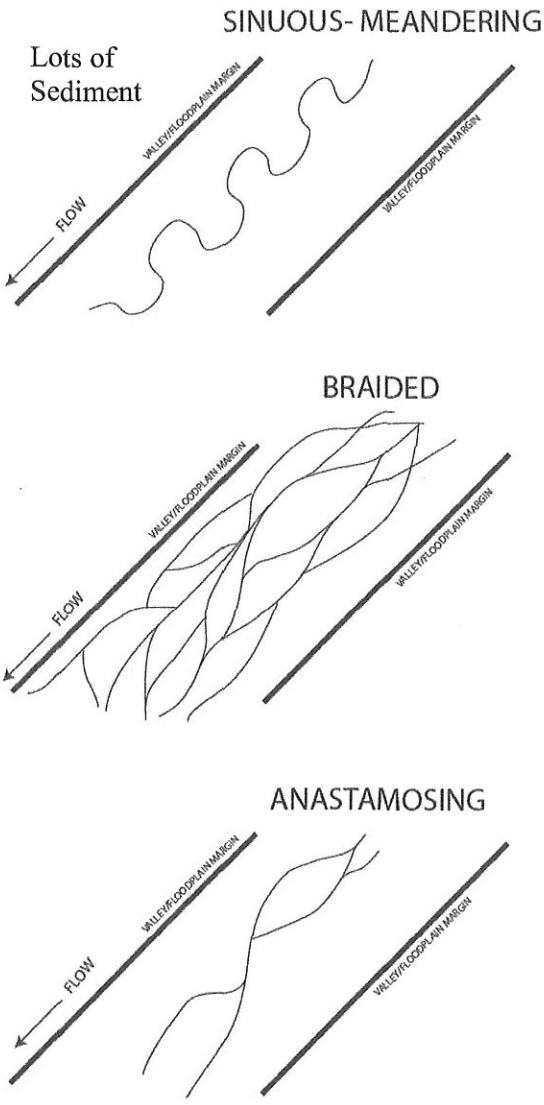


Figure 7-5. Schematic diagrams of the different channel patterns: meandering (sinuous), braided, and anastomosing.

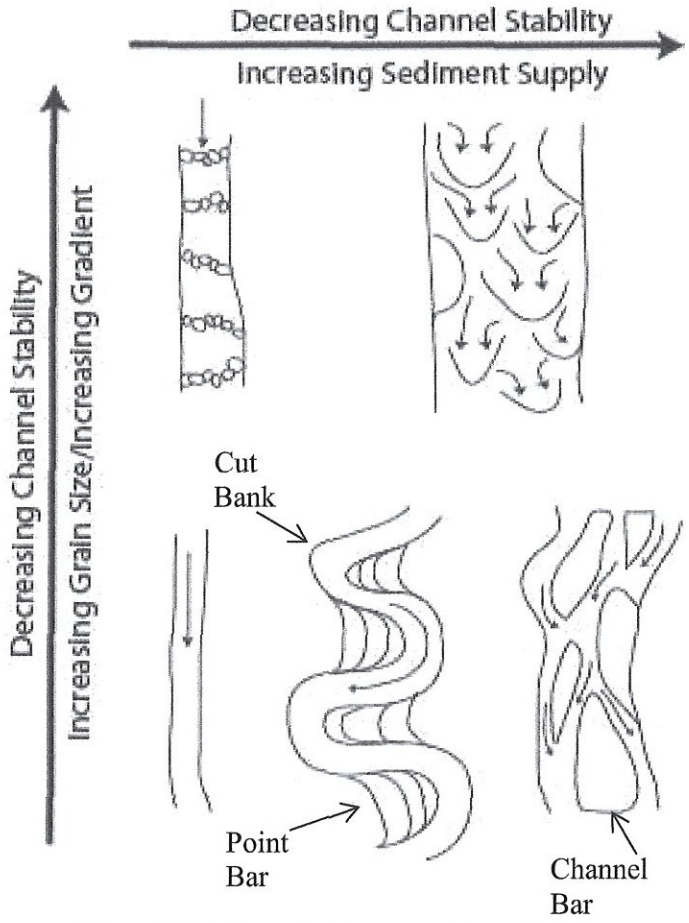


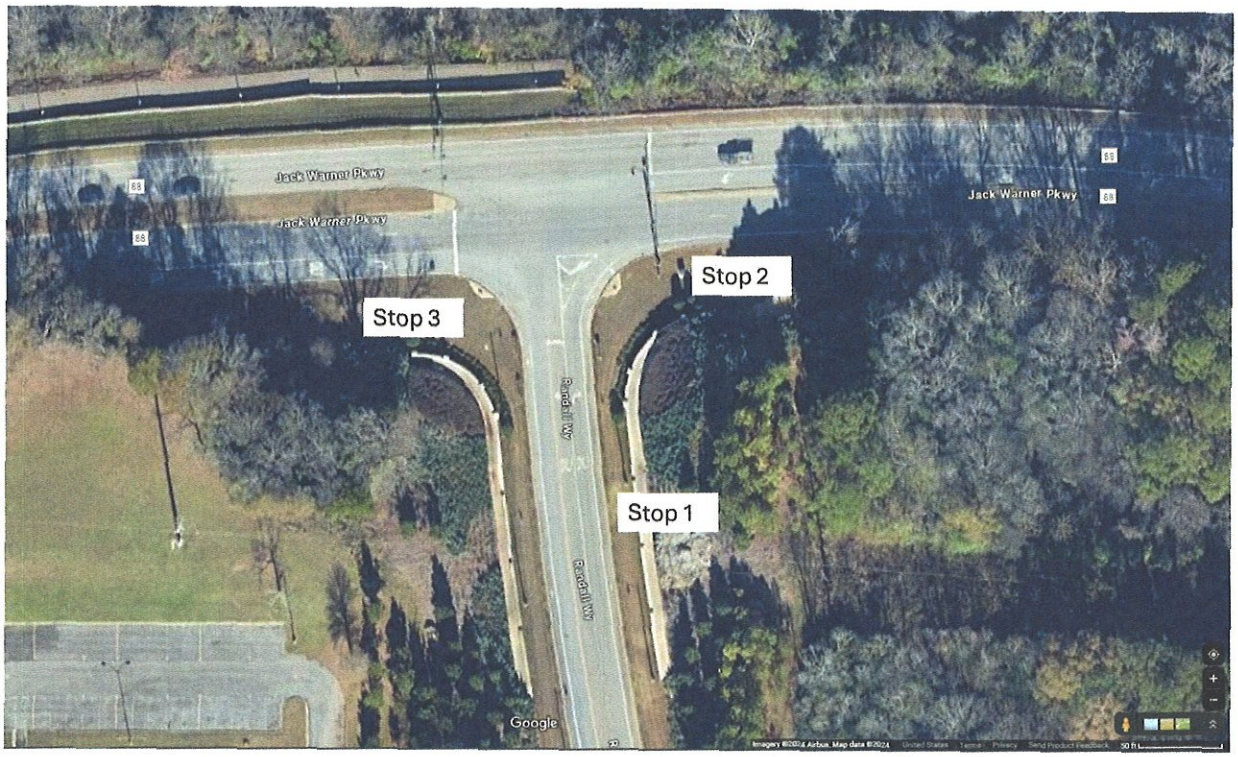
Figure 7-6. Schematic diagrams of the different channel patterns and the relative stability of the channel types with respect to sediment supply, grain size of sediment load and gradient. Modified from Church (1992), modified from Schumm (1985). Top right is a braided stream. Bottom middle is a meandering stream. Bottom right is an anastomosing stream.

Chapter 8: Field Trip

Pottsville Formation along Jack Warner Parkway

An essential part of geology is going outside to observe rocks. Today, you will experience a field trip to help you understand what a geologist does.

SAFETY NOTES: We will be walking to a rock outcrop exposure near Jack Warner Parkway (a 3-stop walk).



Arial image of field area, with localities marked (courtesy of Google.com)

Be aware of:

1. TRAFFIC. Jack Warner Parkway is a high-traffic, high-speed road. Leave ample room between you and the shoulder of the road, and be aware of traffic approaching from behind.
2. As such, **cell phones and earphones/earbuds** may **not** be used while on this field trip.
3. Wear **sturdy, closed-toe** shoes that can get muddy.
4. Be aware of poison ivy. It is present in some areas.
5. Be aware of loose rocks and try to avoid dislodging them. If a rock becomes loose and starts to roll down the hill, alert the group immediately.

Meet your classmates and TA at the location specified by your TA at the beginning of the lab. Your TA will take you to the field and guide you through the lab exercise.

On this trip, you will see exposures of the **Pottsville Formation**. The Pottsville Formation formed during the Pennsylvanian stage of the Carboniferous Period (~300 Ma). A geologic formation is a formally named rock layer that is mappable across a broad area. Formations are defined based on lithology. Rock of a certain lithology is given a formal name that the U.S. Geological Survey of the Department of the Interior approves.

Most formations are made up of sedimentary rock layers or strata, but metamorphic rocks and volcanic rocks can also be labeled as formations.

Annie Edwards

Chapter 9: Topographic and Geologic Maps

Maps have many purposes in geology. How can we locate ourselves in the world? How do geologists know where to look for oil, gas, water, or other resources?

LEARNING OBJECTIVES:

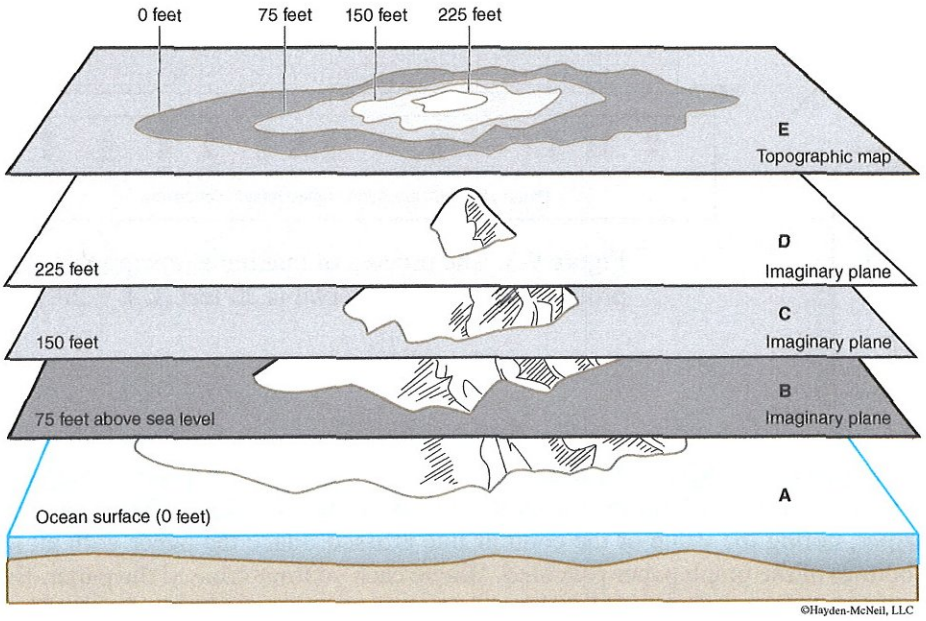
1) Understand how to read a contour map.
2) Understand how to read a geologic map.
3) Contour and map data.
4) Draw a topographic profile from a contour map.

INTRODUCTION:

Geologists are good map readers. A geologist can look at a contour map of an area and immediately visualize what the area looks like in real life. Similarly, a geologist can plot observations of rock types found at the Earth's surface on a map and use 'strike' and 'dip' to project the subsurface. In this exercise, you will be introduced to basic visualization and map-reading skills.

What is a topographic map?

What makes a map a topographic map? By adding contours to our map, we now have a way to indicate **elevations**. A contour is a **line that links points of the same elevation**. If you are walking along a contour line, you will be going neither up nor down. If you want the best workout, you will walk at a right angle to the contour lines. This is the steepest route. Contours follow some basic rules: 1) Contour lines never cross with one exception – an overhanging cliff; 2) Closed contours (i.e., contours that form an irregular closed shape) represent a hill (Figure 9-1) or depression. Closed contours representing a depression usually have hachure marks on the inside of the contour. 3) If the contours are evenly spaced, the slope of the hill is constant. As the contours get further apart, the slope becomes shallower. Steeper slopes are shown by areas where contours are closer together. 4) Where contours cross a stream valley, a V-shape is formed. The V always points upstream.



The lines on surface E are contour lines, and they form a topographic map.

Figure 9-1. This is the method for visualizing a 3D feature on a 2D topographic map.

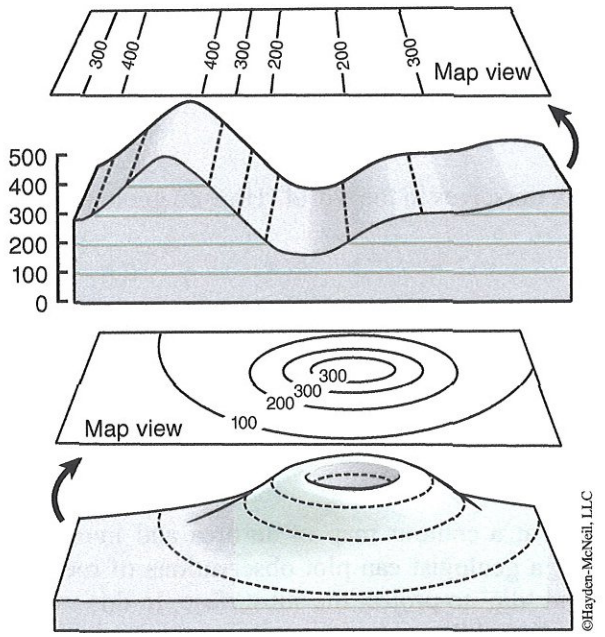


Figure 9-2. This figure illustrates how 3D topography is represented in a 2D topographic map using contour lines. The top two figures depict a hilly region, with the top map view displaying the contour lines that correspond to the dotted lines on the hilly terrain. The contour interval is the amount of feet or meters between each contour line. In both map views, there is 100 feet or meters (it doesn't state which one) between contour lines. C.I. = 100 The bottom figure depicts a volcano with a hollow crater at its summit. The map view shows a circular pattern that corresponds to the dotted lines on the volcano. C.I. = 100

On the topographic map of Figure 9-2, 200 is repeated, and 400 is repeated. What does that mean? The 200-contour line is repeated when going through a low point (like a ditch, valley, or stream), and the 400-contour line is repeated as you go over a hill. Thus, that is another rule – when going through low points or over high points, contour lines are repeated. In the lower example, the contour line 300 is repeated. It is both outside the volcano and inside the volcano, indicating that between the two, there is a hill.

Making Contour Lines

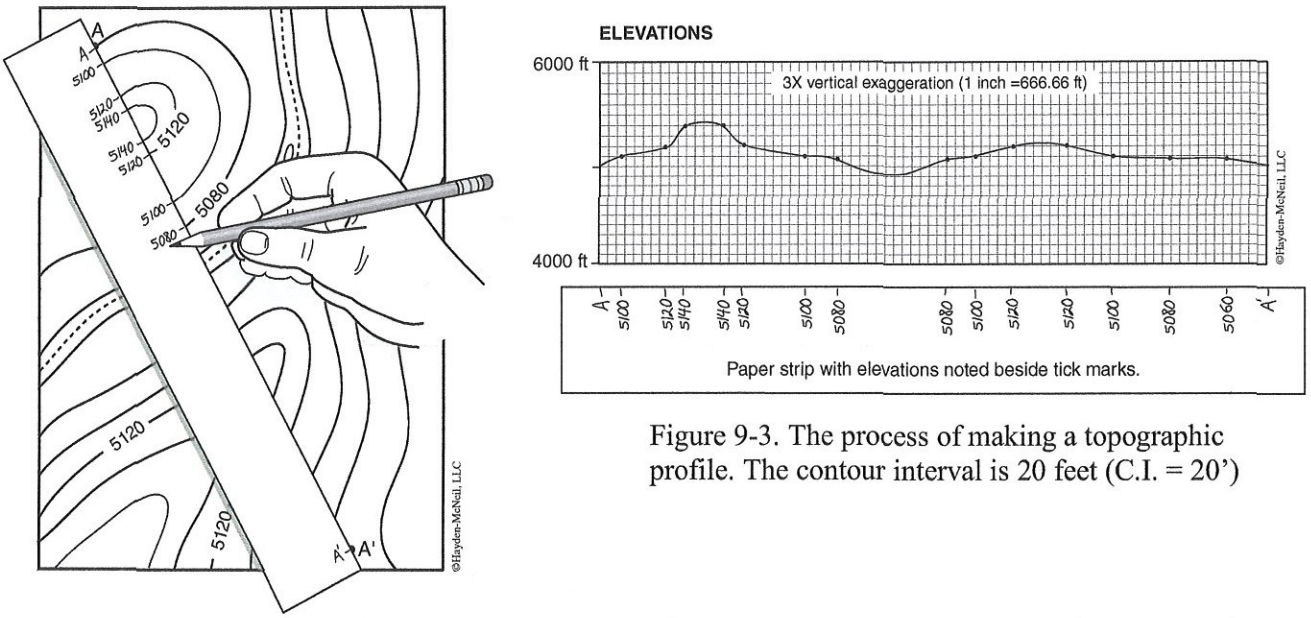


Figure 9-3. The process of making a topographic profile. The contour interval is 20 feet (C.I. = 20')

Use Figure 9-3 to learn how to make a topographic profile. First, lay a scrap piece of paper on top of a topographic map and mark the beginning and end of the profile (A-A' in this example). Mark where a contour line intersects the paper, noting the value of the contour line crossed. Place the paper with all the marks and values along the bottom of the graph paper provided. Where each contour crossed the paper, find that elevation on the graph paper and mark it using the elevations marked on the right-hand side. Then, connect the dots to make a topographic profile. Notice that when you make your tick marks on the paper,

between high points or low points, the contour line repeats, indicating that you have gone over a hill or through a valley (stream or low point).

Map scale: How large an area does my map cover?

A map cannot be the same size as the area it represents on the Earth. Such a map would be more than a little inconvenient to carry. It must be a fraction of that size. Smith Hall is 57 meters long. If we wanted to create a 1/10-scale model of Smith Hall, the long dimension of the model would be 1/10 the actual size of Smith Hall, or approximately 5.7 meters long. The scale of the model to the object is 1:10. This scale is also used in similar systems for maps. A common map scale is 1:24,000. This means that an object on the map is 24,000 times larger in real life. One centimeter on the map corresponds to approximately 240 meters in real life.

What is a geologic map?

Geologic maps represent the type of rock unit that is visible in outcrops at the land's surface. Each color (or pattern) on a geologic map represents a unique lithology and is described in the map legend (Figure 9-4). Other features, such as faults and strike-and-dip measurements, are included and are just as important as the formations. By mapping this information, a geologist can observe the structures and patterns to visualize and assess the subsurface. This is important because we know that certain types of geologic structures are more prone to being reservoirs for natural resources. If a geologist has an idea of the way the feature formed, they will know where to put the most effort into searching for these resources.

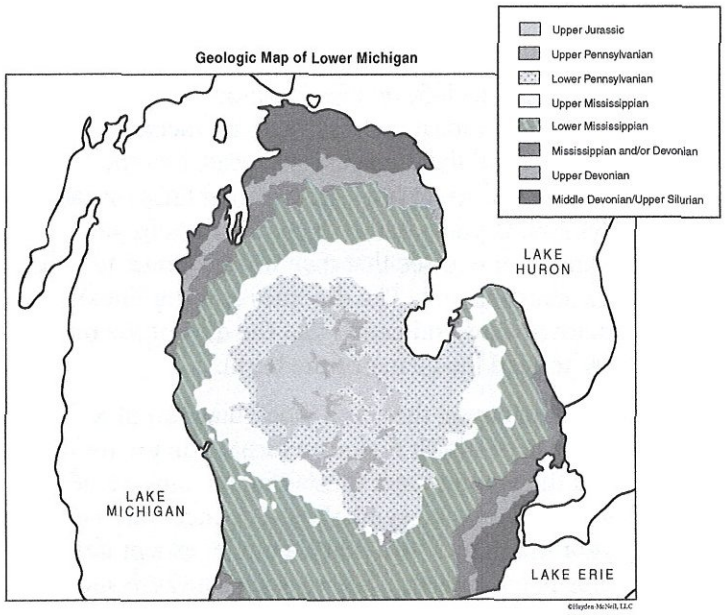


Figure 9-4. Geologic map of lower Michigan. Using the explanation in the upper right, you can see that the different patterns represent the different ages of the rock units. The dotted pattern indicates lakes. The oldest rock is around the edges, and the youngest rock is in the center of Michigan.

What are strike and dip measurements?

We have previously learned that sedimentary rock formations are deposited horizontally. As you will learn in future laboratory exercises, these formations are deformed (squeezed) by many different factors that leave them faulted and folded. When a geologist wants to communicate with another geologist about a particular formation, they measure strike and dip using a 360° compass. **Dip** is the angle by which the bed is tilted from horizontal (see Figure 9-5). We note both the direction of dip and the angle of dip. **Strike** is always perpendicular (90°) to the direction of the dip. Do not confuse this with the actual dip measurement. Strike is read from the flat compass that is held to point perpendicular to the dip direction. Together, strike (the long line) and dip (the short line) are plotted on a geologic map where they were taken. When viewing a completed map area, a geologist can identify geologic structures without needing topographic contours.

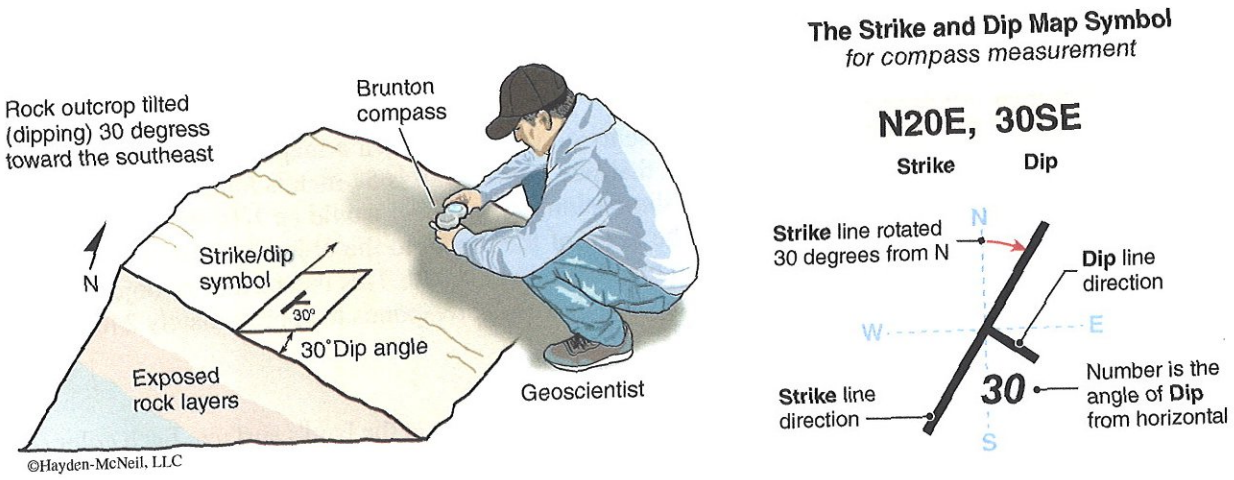


Figure 9-5. A geoscientist is measuring strike and dip on a rock surface. The measurement was N20E, 30°SE. To a geoscientist, this describes exposed rock layers that are dipping 30° in the southeast direction (indicated by the short line to the right of the figure). The strike is 90° to that (long line to the right of the figure).

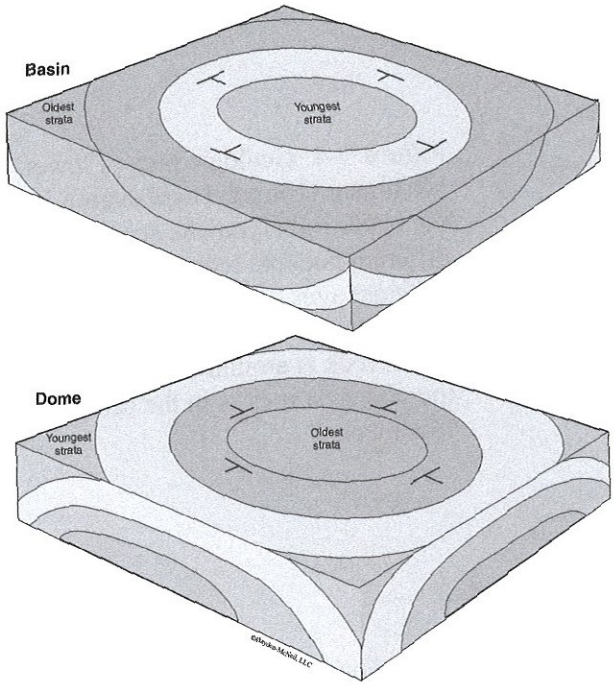


Figure 9-6 Combining strike and dip and geologic maps. To the left, on top, is a block diagram of a basin. The oldest rocks (strata) are located on the outside, and the youngest are located on the inside. The strike lines are the long lines on each symbol. If you connect the strike lines in your mind, you will see that they form a circle, just like the strata pattern. The dip lines (shorter lines) point inward, indicating that the dips of the rocks are toward the center of the basin.

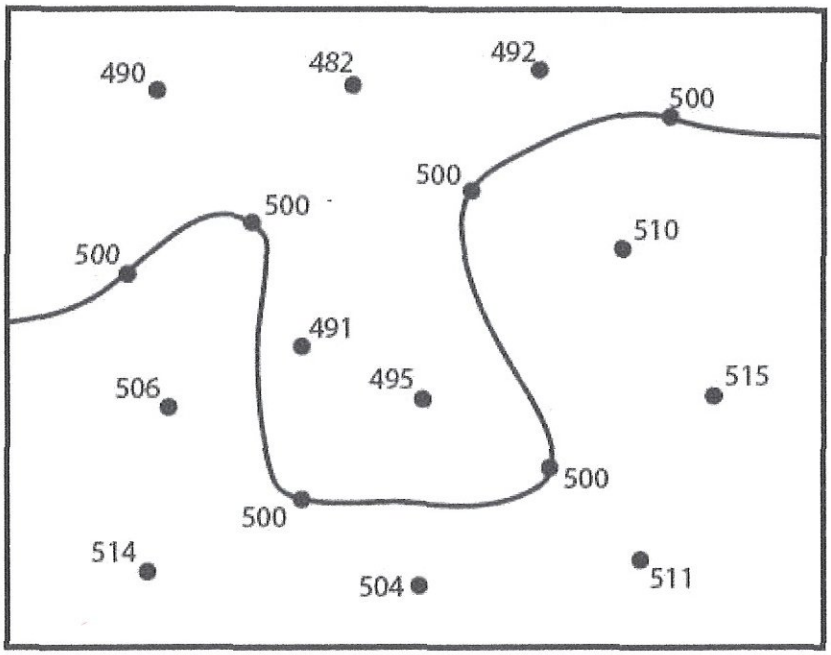
On the bottom, there is a block diagram of a dome. The oldest rocks are located on the inside, and the youngest are located on the outside. If you look at the strike symbols and connect them in your mind, they still make a circle, except now the dips point outward. The rock dips away from the center of the dome. You can think of a dome like an upside-down bowl.

NAME _____

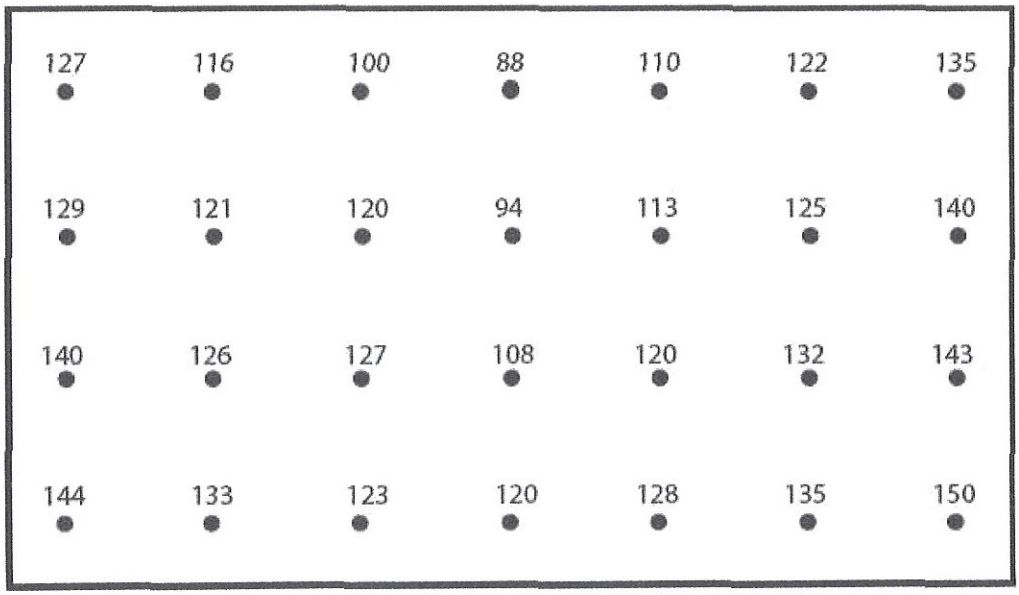
Topographic and Geologic Maps

Making Contour lines

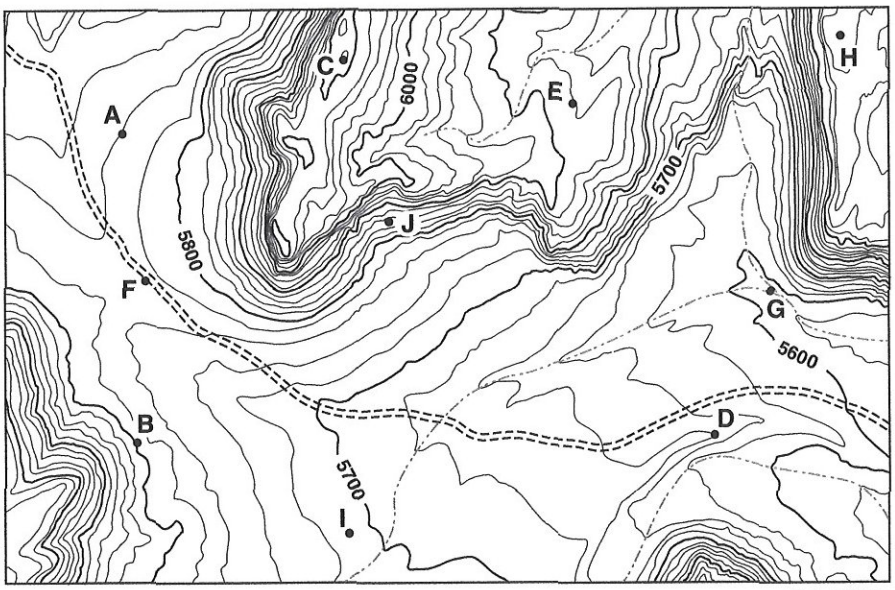
1. Contour the map below with a contour interval of 10 m (C.I. = 10 m). One contour has been drawn to help you begin. (10 points)



2. Contour the map below with a contour interval of 10 m (C.I. = 10 m). (10 points)



Reading a topographic map (21 points)



©Hayden-McNeil, LLC

Map 1

Remember that contour lines are lines of equal elevation. Refer to Figure 9-1 and the words above that figure. The double dashed line indicates a dirt road. Streams are indicated by the gray dash-dot-dot pattern. Remember that when crossing a stream, a contour line V's upstream. The numbers indicate the elevation of that contour line in feet. North is toward the top of the paper.

3. In between two of the heavy black contour lines, how much elevation is there? _____
4. In between two of the heavy black contour lines, how many lighter contour lines are there? ___
5. Thus, what is the contour interval of this map? _____
6. By each letter, tell me what the elevation is where the dot is located. If the dot of the letter is in between two contour lines, you will need to estimate the elevation.

A _____ B _____ C _____ D _____ E _____

F _____ G _____ H _____ I _____ J _____

7. Point F is on a road and is located at a geographical point that is important if you are going to read this map correctly. The contour lines to the left and right of point F are the same. One rule is that if you go over a low point or a high point, the contour line will repeat. Figure 9-2 shows this. Now that I have drawn your attention to that point, what is the value of the repeated contour line?
_____ (You might want to reevaluate your value of point B above).

8. What is the highest elevation on the map?

9. What is the lowest elevation on the map?

10. Around letter A, the contour lines are far apart. What does that indicate?

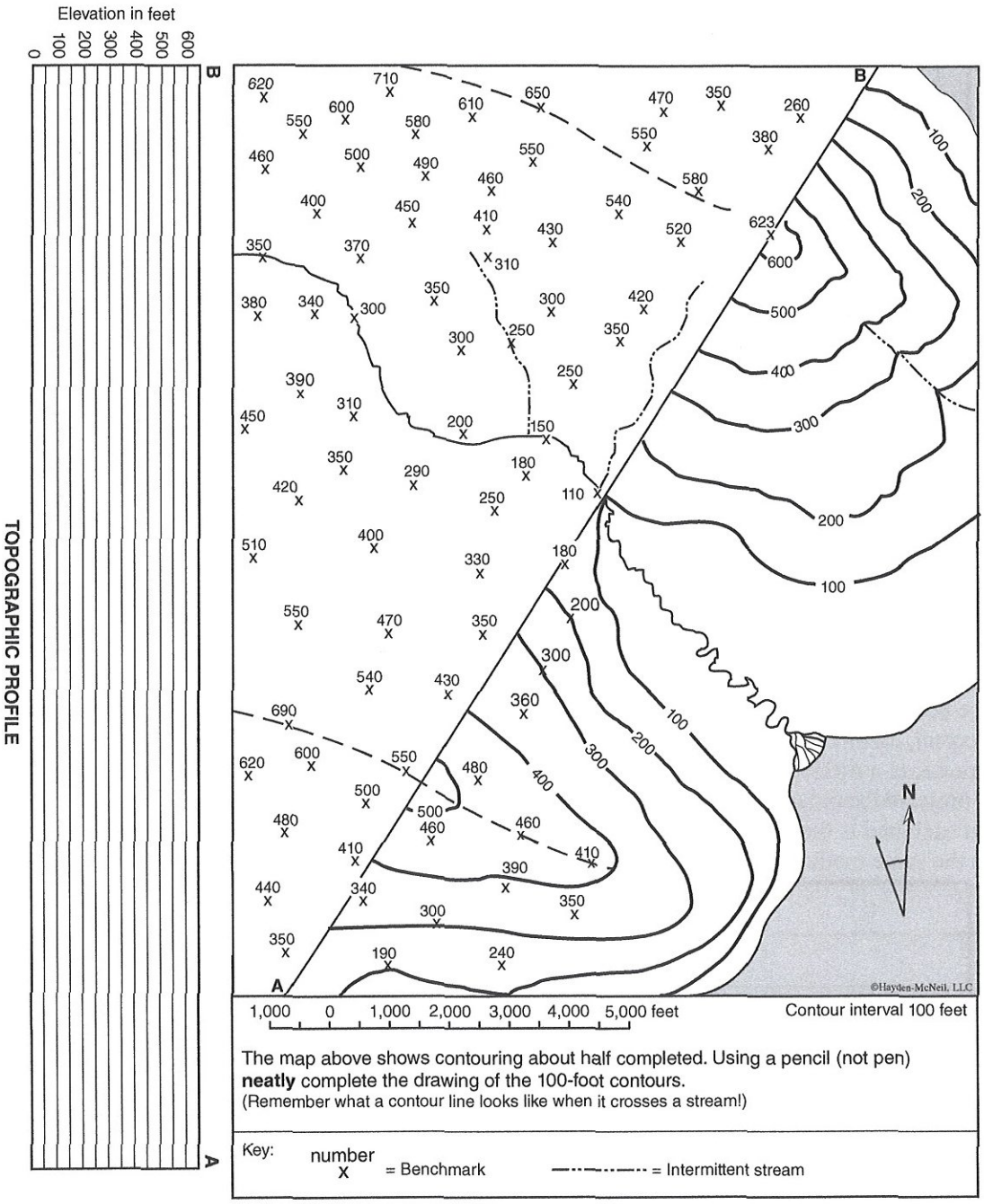
11. Around letter J, the contour lines are close together. What does that indicate?

12. Between points G and H, what does the topography look like?

12. Why was the road built where it is right now?

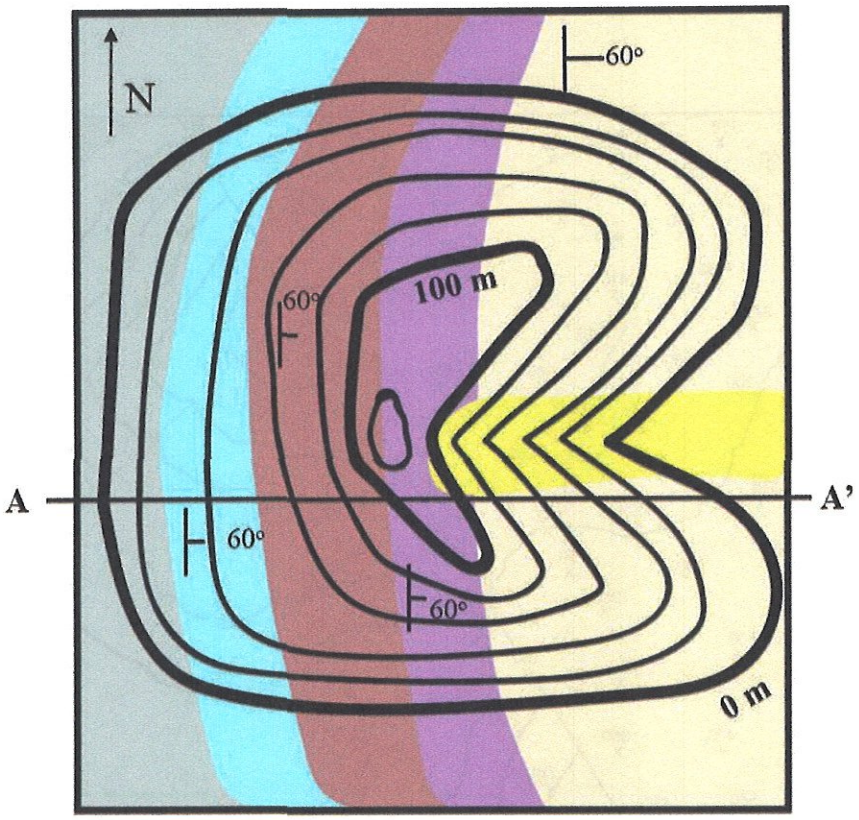
13. What is the name of the geographic feature at F? You can just describe if you don't know the word.

Turning contour lines into topographic maps and making a topographic profile.

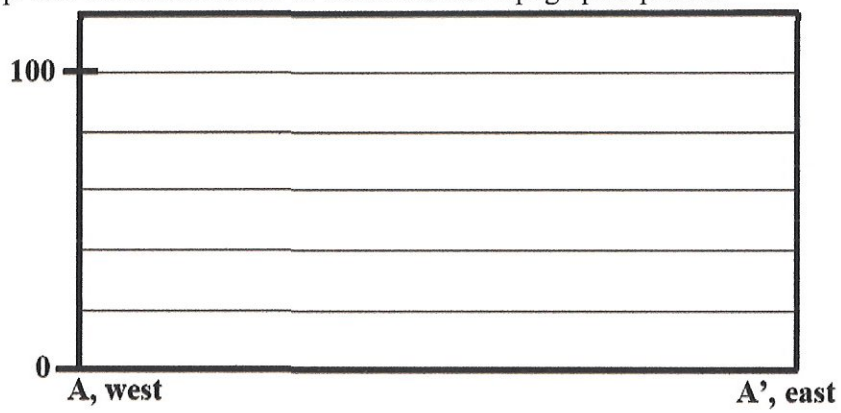

Elevation in feet
0 100 200 300 400 500 600
B
A
TOPOGRAPHIC PROFILE
B
A
N
©Hayden-McNeil, LLC
1,000 0 1,000 2,000 3,000 4,000 5,000 feet
Contour interval 100 feet
The map above shows contouring about half completed. Using a pencil (not pen) **neatly** complete the drawing of the 100-foot contours.
(Remember what a contour line looks like when it crosses a stream!)
Key: number X = Benchmark
= Intermittent stream

14. Finish the left side of the contour map above using a pencil. When a contour line crosses a stream, it v's upstream. Next, along the profile A-B, draw a topographic profile. Use the method shown in Figure 9-3. (25 points finishing the map, 15 points for the topographic profile)

15. Figures 9-2 and 9-4 combine geologic maps and strike and dip. Is Figure 9-2 a dome or a basin, and how do you know? (2 points)



6. In the space below, first draw a topographic profile along profile A-A'. Fill in the missing elevations on the y-axis. Second, assume that the colored formations on the map are all dipping at a 60 ° angle. Each of the colors represents a different rock unit. Fill in the inside of your profile with the appropriate color to represent the projected geologic formations based on the information available on the map, keeping in mind that the dip of each bed is the same. (15 points). The yellow is only surface dirt and does not need to be on the map. Use the same method as above for this topographic profile.



17. What is the contour interval of this map? (1 point_____
18. Which direction are the beds dipping? (1 point) _____

Chapter 10: Hydrogeology

The water we drink is groundwater. Where does it come from? How does it move? Will we run out of fresh water? These questions are pertinent to our everyday lives. Let's learn a little bit about what we consume every day.

Learning Objectives:

1) Identify and understand basic hydrogeology terms and concepts
2) Understand potentiometric surface relationships and water-table relationships.
3) Understand how the potentiometric surface & watertable relate to specific types of aquifers.
4) Understand concepts related to water level, land surface, and water elevation in water wells.
5) Construct a water table contouring map (groundwater elevation contour map) from well data.
6) Construct groundwater models to evaluate how geology materials affect groundwater flow.

MATERIALS: BRING YOUR LAPTOP, pencil, paper, ruler, calculator.

INTRODUCTION:

Hydrogeology is the study of groundwater, or the study of water in the subsurface. Many different facets of hydrogeology include understanding the movement of water through geologic material, evaluating groundwater as a resource, determining the availability of present and future water supplies, assessing the movement of contamination in groundwater, developing remediation technologies to clean up polluted groundwater, understanding relationships between rainfall and groundwater, and developing water management strategies.

Why is groundwater important? Groundwater provides the largest amount of fresh water available to humans. We depend on groundwater every day for drinking water, food production, and industrial processes. Of all the Earth's freshwater resources, groundwater makes up about 14% of the total, with glaciers and ice sheets making up about 85%. However, glaciers and ice sheets are not readily available to humans because they exist as snow and ice. Therefore, if we exclude glaciers as a viable freshwater source, groundwater supplies approximately 94% of the readily accessible freshwater available to humans. In stark contrast, rivers, streams, and lakes account for only 0.5% of the total freshwater on Earth. Groundwater makes up about 22% of the world's freshwater supply. In the U.S. alone, over 60% of the population depends on groundwater (public water supply) for its drinking water needs (USGS, 1995). Additionally, over 40 million people in the U.S. obtain their drinking water from domestic groundwater wells. In Alabama, over 50% of the people acquire their drinking water from groundwater. Groundwater is and will continue to be increasingly sought after as demands for clean freshwater resources increase due to population growth, urban and rural sprawl, commercial agriculture practices, and pollution. Of course, groundwater resources can be depleted directly through overexploitation and unsustainable extraction practices, but they can also become unusable if contaminated by pollution.

BACKGROUND:

Hydrogeologists utilize a range of disciplines, including geology, environmental science, hydrology, soil science, engineering, biology, and policy and management, to address complex problems. One of the most notable hydrogeologists of the mid-nineteenth century (i.e., the 1850s) to study groundwater flow was the French scientist Henry Darcy, who first devised an expression to calculate groundwater flow as it relates to the geologic media through which it flows. Many other notable scientists have gone on to further the understanding and development of the field, including well hydraulics behavior, contaminant transport, and computer modeling. For this lab, however, we will focus on the groundwater expression that Henry Darcy himself developed.

An 'aquifer' is defined as a geologic stratum that is completely saturated with water and sufficiently permeable to transmit economic quantities of water to wells and springs. A "good" aquifer is a result of many important factors, such as permeability and porosity. The most important factor defining whether a geologic unit will serve as a "good" aquifer is permeability. Permeability is the ability of a geologic stratum to transmit water, or it describes the ease of water flow through a geologic medium (Figure 10-1). Excellent aquifers typically have high permeabilities. Also of importance is the porosity, which is defined as the percent (%) of pores space available for water to reside or, alternatively, the ratio of void spaces in a rock or sediment to the total volume of the rock or sediment (Figure 10-1). The porosity gives us an idea of how much water can be stored within a certain volume of geologic media. However, a geologic material with a high porosity does NOT necessarily have a high permeability.

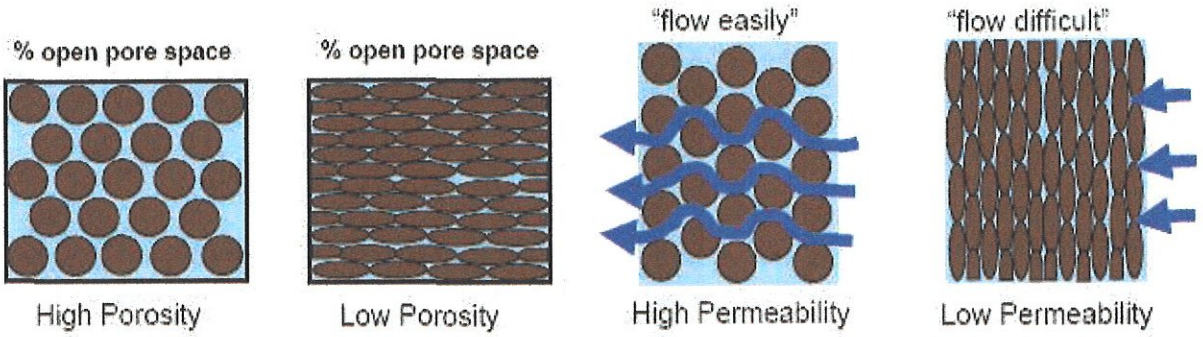


Figure 10-1: A schematic depicting the differences between Porosity and Permeability.

In addition to permeability and porosity, we also use hydraulic conductivity (K) to describe how well a fluid moves through a particular geologic stratum. The hydraulic conductivity is used to describe the physical characteristics (i.e., shape, packing, etc.) of the sediment and the characteristics of the fluid (i.e., density, viscosity, etc.) flowing through the sediment or geologic stratum. In other words, hydraulic conductivity (K) is a lumped term used to describe geologic media in terms of their ability to allow a fluid to flow through them. A high K value would represent a geologic medium with relatively high permeability, and therefore it would serve as a "good" aquifer. A low K value would represent a sediment or geologic medium that has relatively low permeability and would NOT make a "good" aquifer. Geologic sediments or strata that transmit water very slowly (very low permeability) are defined as aquitards. These geologic units restrict the flow of water and are typically associated with clay layers in the subsurface. In some cases, these clay layers (i.e., aquitards) can confine ("sandwich") aquifers (permeable units) between aquitard layers (see later discussion on aquifer types).

Different types of aquifers exist within the subsurface. Aquifers are continually receiving water in some regions and losing water in others. The water in an aquifer can be depleted if it is losing more water than it is receiving. Conversely, if more water is being added to the system than is being withdrawn, then the water in the aquifer will increase. If the aquifer system is in balance or sustainable pumping practices are maintained, then there will be no net gain or loss of water in the aquifer, and the system will be in equilibrium. The process by which water adds to the aquifer is known as recharge. For example, when precipitation occurs, a certain fraction of that water infiltrates into the ground and percolates downward through the unsaturated zone. The unsaturated zone is the portion of the subsurface that extends from the land surface to the water table, and a significant fraction of air exists within the pores. In this unsaturated zone, the pore spaces between the sediment or rock are partially saturated with water (i.e., air and water exist within the pores). As water percolates downward through the unsaturated zone (also known as the vadose zone), it reaches the water table, where it contributes to the aquifer or is said to recharge the aquifer. The water table is defined as the surface below which all pore spaces between sediment or rock are completely saturated (full of water), and the fluid pressure along this surface is equal to atmospheric pressure. More simply, the water table is the surface that joins the unsaturated zone and the saturated zone.

The saturated zone is the region in the subsurface where all the spaces in a sediment or rock are full of water. The saturated zone is the entire region below the watertable where groundwater is stored and transmitted (groundwater flow). An important concept opposite to recharge is the process called discharge. Discharge is defined as the removal of water from the saturated zone or the aquifer. For example, groundwater that flows to springs, rivers, or lakes would be discharging from the aquifer or groundwater. Also, discharge is occurring when wells extract (pump) water from an aquifer (saturated zone). In these cases, water is being removed from the aquifer (discharging) to supply water to springs, rivers, lakes, and water wells.

Aquifer Types

Two types of aquifers exist: unconfined aquifers and confined aquifers. Unconfined aquifers, also called water-table aquifers, are permeable saturated geologic strata that are NOT confined ("bound") by aquitards and are closest in proximity to the land surface. The upper surface of unconfined aquifers is represented by the water table or the bottom of the unsaturated zone. In other words, the watertable will be present within the uppermost unsaturated zone of the aquifer. Direct precipitation and infiltration can eventually recharge these aquifers. If a water well is drilled into the unconfined aquifer, the water level that rises in the well will be equivalent to that of the water table below the surface. Therefore, a water-well constructed into an unconfined aquifer is known as a water-table well. A water well is an artificial cylinder structure that is drilled and emplaced into the subsurface, which allows water to be extracted from the aquifer. Confined aquifers, on the other hand, exist below unconfined aquifers and are confined ("sandwiched or bound") between two aquitards. This "sandwiched" or confined configuration imposes a significant pressure on the water within the confined aquifer. If a well is drilled and emplaced into a confined aquifer, the water level in the well can rise even above the land surface, in which case water will flow freely from the top of the well (at the land surface). Why?? This water that is under pressure can now "escape", flowing up through the well. When water flows freely to the surface from a well, the system is said to be artesian, and it is called an artesian well. The water level in the water well does not necessarily have to rise all the way to the land surface. The height to which the water level will rise in the well is dependent on the pressure within the confined aquifer. In either case, the level to which water rises in the water well in the confined aquifer is represented by what is called the potentiometric surface; this is not the same as the water table. A flowing artesian well occurs when the potentiometric surface is higher than the land surface, and water flows freely from the well above the land surface. A non-flowing artesian well occurs when the potentiometric surface is at or below the land surface, and the water in the well does not readily flow from the well to the land surface. Recharge to confined aquifers through precipitation and infiltration may occur very far from the region.

Measurements in Wells

Hydrogeologists often measure the water level in water wells to assess the amount of freshwater available for drinking and consumption, and to determine whether the water table is declining or increasing. A common measurement made in the field is determining the depth to water in the water well. This is accomplished by measuring the distance from the top of the well (i.e., the land surface) to the water level in the well. The top of the well (i.e., land surface) is also considered the wellhead. The wellhead elevation is the elevation, above mean sea level, of the top of the well ("wellhead"). The water level elevation (groundwater level) refers to the water level elevation, measured with respect to mean sea level, in a water well. The water level elevation (WLE) is determined by subtracting the depth-to-water (DTW) from the wellhead elevation (WE).

$$WLE = WE - DTW$$

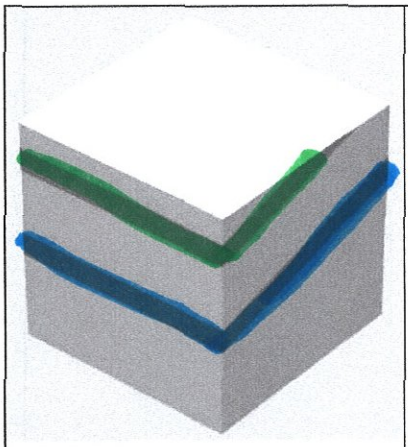
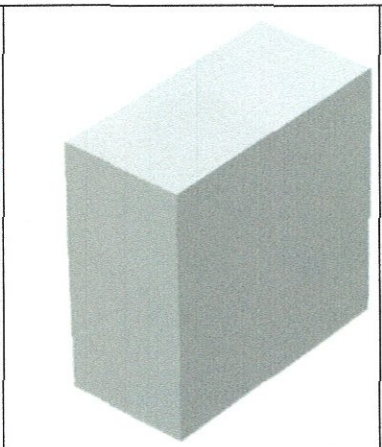
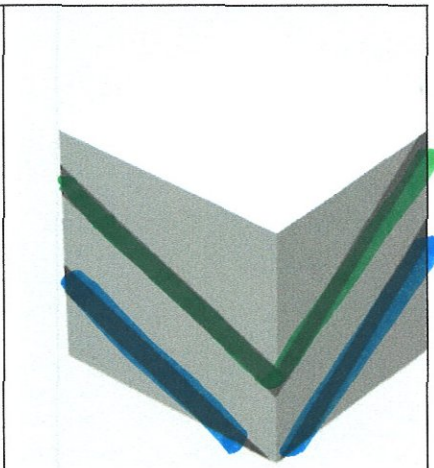
Water level elevation wellhead elevation Depth to water

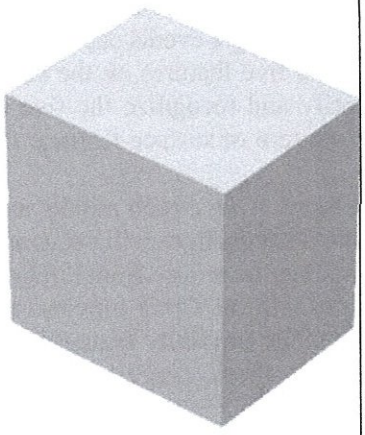
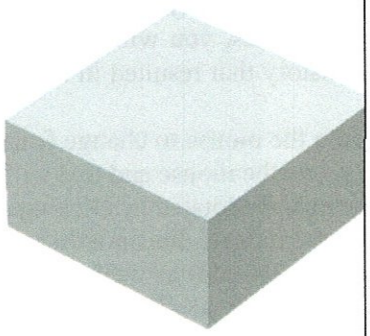
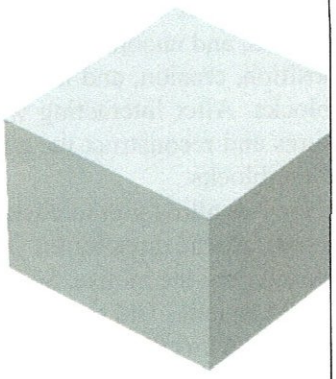
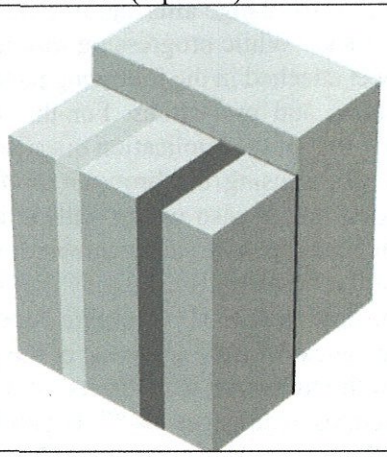
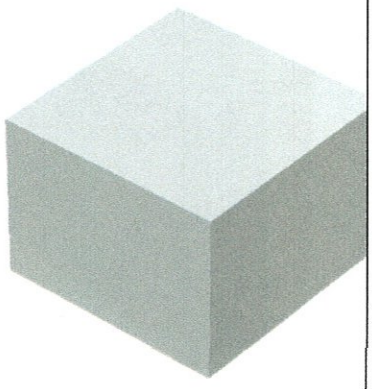
DEFORMATION LAB – PRE-LAB HOMEWORK **(26 points)**

Blocks Module Student Guide: You will learn about five major geologic features - layers, folds, faults, intrusions, and unconformities. Throughout the module, you will learn how geologic events such as tilting, deposition, erosion, and faulting change and modify the appearance of these five features on the surfaces of blocks. After interacting with these movies, you will be able to identify and recognize the five main features and reconstruct the geologic history that resulted in the complex pattern of surface features found in these blocks.

The movies allow you to click-and-drag the mouse to change features in them. Above each movie, arrows will indicate the direction(s) you can move the mouse and text will indicate what changes will occur as you click and drag the mouse. Some movies can be rotated by clicking and dragging the mouse from left to right (or right to left). The slower you drag the mouse, the smoother the changes will be. Other movies let you rotate a block (clicking and dragging side-to-side) as well as making the block **partially transparent** so you can see features beneath the surface. For movies with two changes in them, dragging the mouse diagonally will cause both changes to occur simultaneously. To prevent this, try to drag the mouse horizontally and then vertically (or vertically and then horizontally). Other movie types in this module allow you to: **cut into a block** so you can see how erosion would change the surface of a block; **offset a fault** to observe how layers or folds would appear to change after faulting occurs; **reveal an unconformity** to see the boundary between old and young rocks. While progressing through this module, you will be asked to complete various activities on worksheet attached in the following pages. This module was designed to help you form your own definitions of terms and procedures. For this reason, answers will not always be provided for confirmation. The same is true of the application questions at the end of each section.

Go to http://reynolds.asu.edu/ This works using the browser Firefox, but the movies may not work; however, you can still answer the questions. It also works with Internet Explorer and Google Chrome; however, if the click on the movies, they will open in a different window. You must open the movie window on the computer (bar at the bottom of the browser). I used a PC but if it doesn't work, try a Mac. On the left-hand side menu in purple, click on **Interactive 3D Geologic Blocks**, then click **Abbreviated Module** on the left side bottom of the page; then click **Module** at the top of the page. Work through these interactive 3-D blocks and place your answers on the following worksheets by filling in the blank spaces. If you need some explanation about geologic structures, read pages 84-87. **If you do not finish in the time allotted in the visualization laboratory, finish these exercises at home and bring it to lab next week.**

		
L-1 Sketch (2 points)	L-2 Sketch (2 points)	L-3 Sketch (2 points)

		
F-1 Sketch (2 points)	F-2 Sketch (2 points)	F-3 Sketch (2 points)
Direction of faulting: Visual clues used:		
Ft-1 Describe (2 points)	Ft-2 Sketch (2 points)	I-1 Describe (4 points)
1. 2. 3. 4.		
I-2 List Order of Events (old to young) (4 points)	U-1 Sketch (2 points)	

Chapter 11: Deformation

If rocks are deposited horizontally, why do we observe rocks tilted on end and smashed up like an accordion?

Figure 11-1. Folded sedimentary rocks.

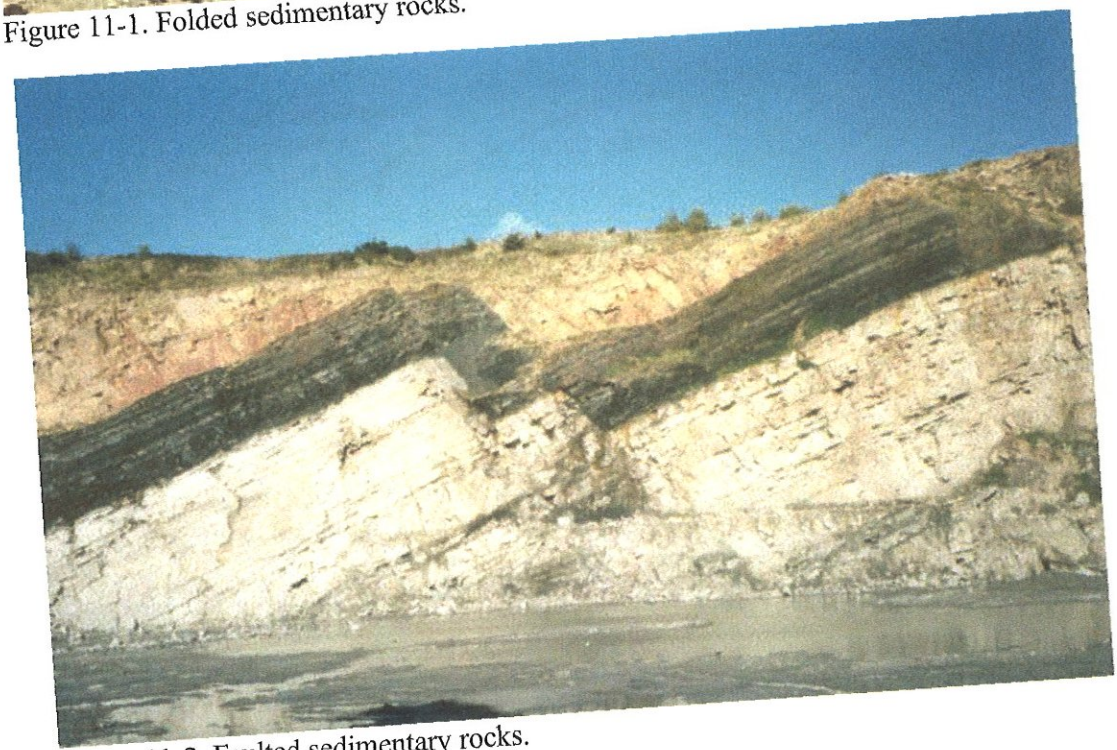


Figure 11-2. Faulted sedimentary rocks.

LEARNING OBJECTIVES:

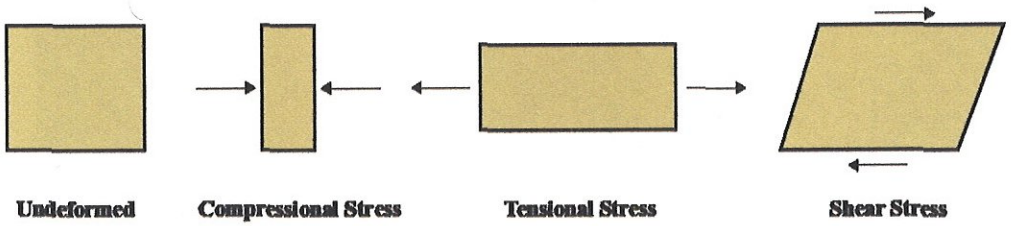
1) Understand the different types of faults and folds.
2) Understand and use strike and dip to describe faults and folds.
3) Enhance 3-dimensional viewing.
4) Use computers to help you understand faults and folds.

MATERIALS

Colored pencils, protractor, ruler

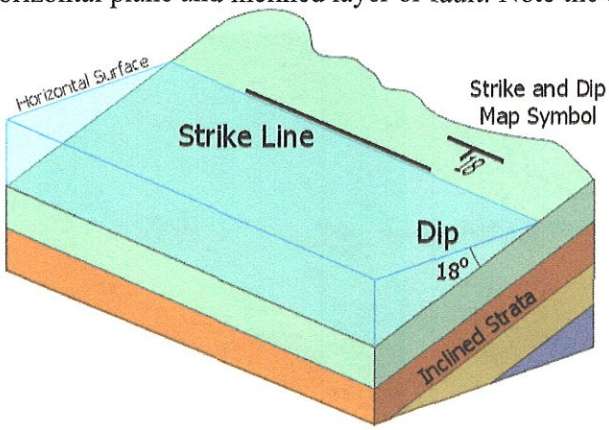
DEFINITIONS

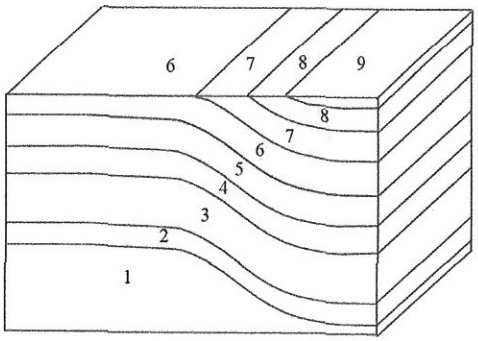
Stress: force applied over a given area. There are three kinds of stress: 1) Tension – causes lengthening; 2) Compression – causes shortening; 3) Shear – causes tearing and smearing. If an undeformed cube (on the left) is subjected to stress, it is deformed. If that cube is compressed, it becomes shorter (left center). If that cube is under tension, the cube is pulled apart or extended (right center). If that cube has its top part pushed to the right, it is sheared (on the right).



Strike: the compass bearing of a line formed by the intersection of a horizontal plane and an inclined layer. Note the strike line on the rock.

Dip: the angle between a horizontal plane and inclined layer or fault. Note the dip line and dip angle.

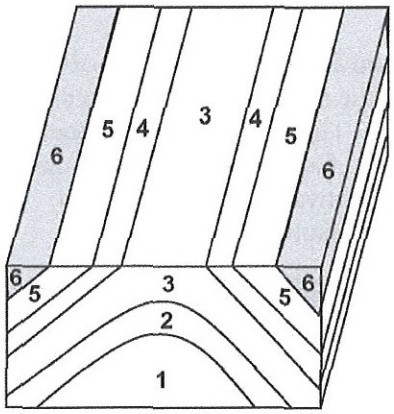


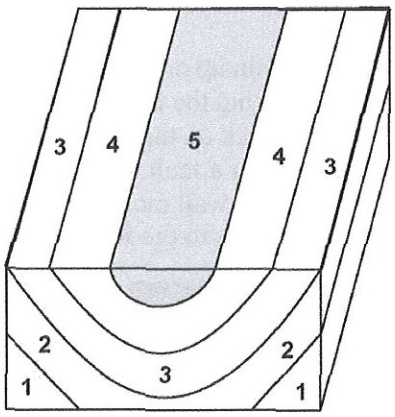


FOLD: rock layers that have been compressed, causing them to bend in different directions.

Monocline: To the left is one type of fold called a monocline. A monocline only had one limb where the rock layers are bent.

Two other types of folds are antiforms, which form an upside-down U, and synfoms, which form a U. When the age of the folded rocks can be determined then they are termed anticlines and synclines. Anticlines and synclines have two limbs.

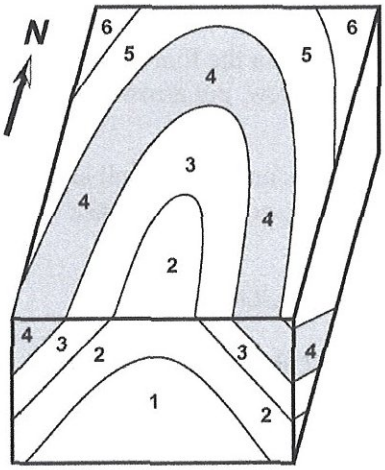


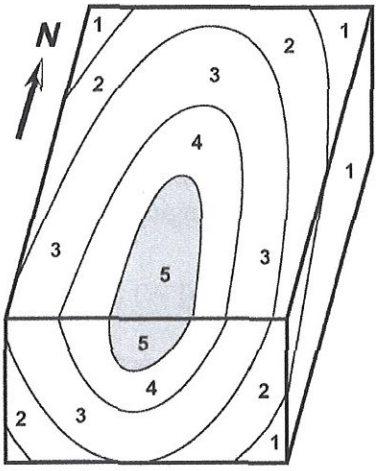


ANTICLINE SYNCLINE 1 = oldest; 5 = youngest

In map view, an **anticline** reveals older rock layers in the core and younger layers on either side. The strike and dip symbols point away from one another. The map pattern produced by a **syncline** has younger layers in the core and older layers on either side. The strike and dip symbols point toward one another.

With your TA: Add 4 Strike and Dip symbols to the block diagrams above.





PLUNGING ANTICLINE PLUNGING SYNCLINE **1 = oldest 5 = youngest**

A **plunging anticline** – oldest rock at the core of the fold, strike and dip symbols point away from one another and wrap around the structure. The nose (or apex) of the fold points in the same direction as the plunge of the fold axis. On the left diagram the plunge is toward the North. How do you know it's an anticline?

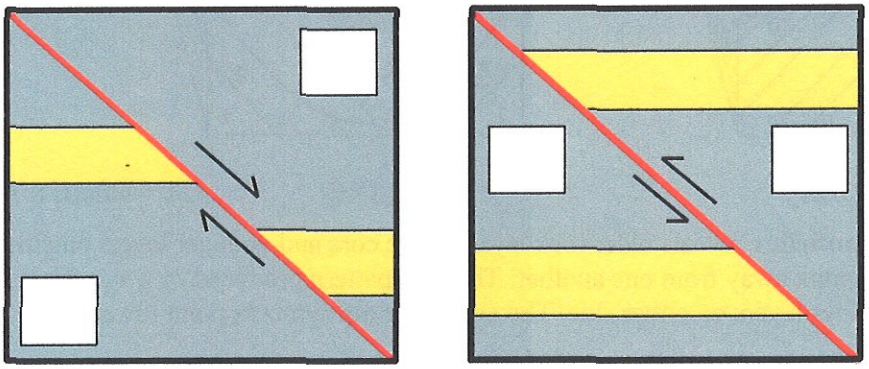
A **plunging syncline** – youngest rock at the core of the fold, strike and dip symbols point away from one another and wrap around the structure. The nose (or apex) of the fold points toward the open part of the fold (opposite the anticline). On the right diagram, the plunge is toward the south. How do you know it's a syncline?

With your TA: Add 4 Strike and Dip symbols to the block diagrams above.

Two other folds are a **dome and basin**, which are illustrated in Figure 10-6.

FAULT: is a discontinuity in a rock, in which there has been observable displacement. There are two types of faults, (1) dip-slip and (2) strike-slip.

Dip-slip faults are faults that have motion up or down the face of a fault, and are either normal dip-slip faults or reverse dip-slip faults. Classifying the fault depends on the dip of the fault and the location of the hanging wall and footwall. The fault block on top is called the hanging wall. The fault block on bottom is called the footwall. To determine whether a fault is a normal or reverse fault, first you must identify the hanging wall and footwall. If the hanging wall moves down relative to the footwall then it is a normal fault. If the hanging wall moves up relative to the footwall then it is a reverse fault.



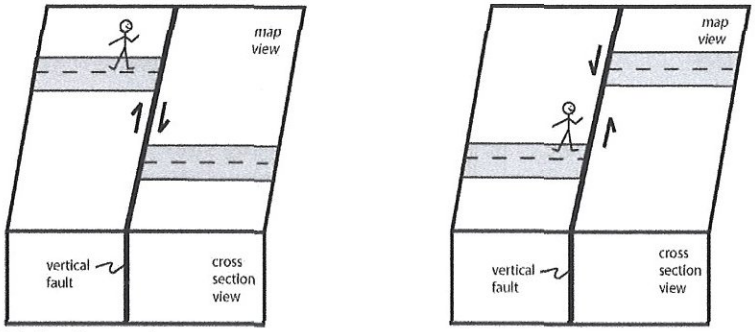
Normal Fault **Reverse Fault**

Normal Fault – hanging wall moves down relate to footwall, exposes older rocks on the footwall and younger rocks on the hanging wall; symbols go on the hanging wall side in map view, put arrows on the cross-section side, caused by tension.

Reverse Fault – hanging wall moves up relate to footwall, exposes younger rocks on the footwall and older rocks in the hanging wall; symbols go on the hanging wall side in map view, put arrows on the cross-section side, caused by compression.

With your TA: Add hanging wall (HW) and footwall (FW) to both of the block diagrams.

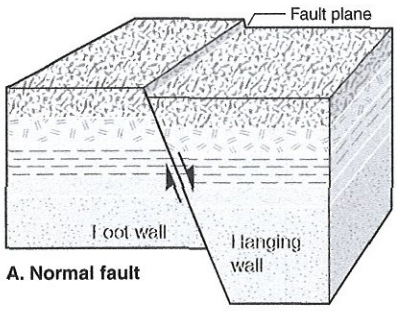
Strike-slip faults occur when rock units move past one another, caused by shear stresses. Strike-slip faults are usually vertical; they do not have a hanging wall or footwall. Motion is defined as either right-lateral or left-lateral.



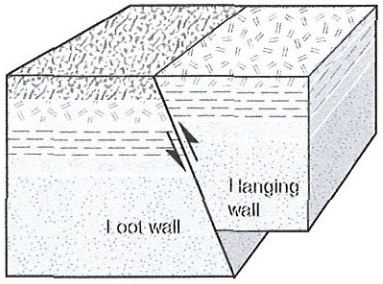
Right-lateral **Left-lateral**

Examples are shown on the next page of the different faults with the footwall and hanging wall illustrated. The top of each block diagram is a map view. The front side of each diagram is called the cross-sectional

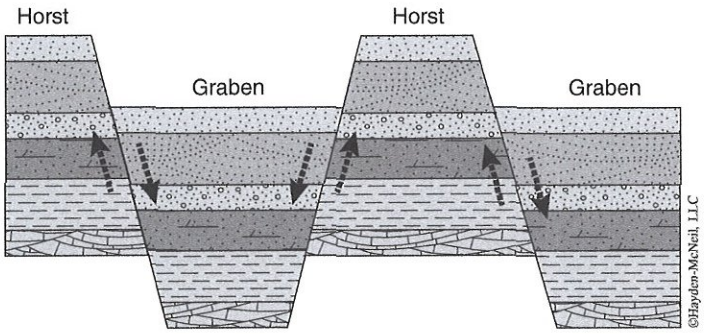
view. A: Normal fault: note that in the cross- sectional view, the hanging wall is pushed down relative to the footwall. B: Reverse fault: note that in the cross –sectional view, the hanging wall is pushed up relative to the footwall. C: Strike-slip fault: note that in the cross-sectional view, the units do not show much difference from one side of the fault to the other, but in the map view, you can see the black intrusion is moved from one side relative to the other.

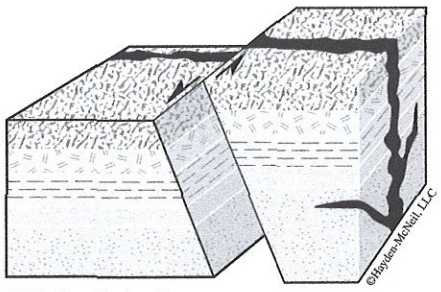


A. Normal fault



B. Reverse fault

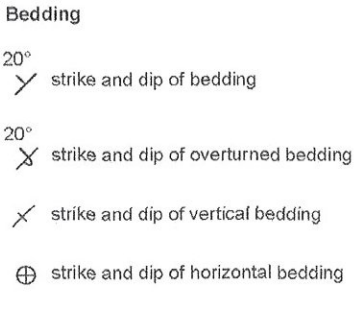


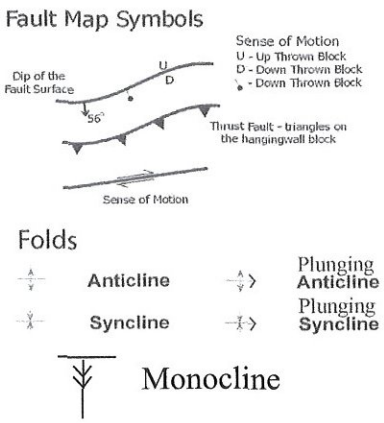


C. Strike-slip fault

Lower right shows a horst and graben system with normal faults.
In the C illustration, is this strike-slip fault, right-lateral or left-lateral? _____

Map Symbols:

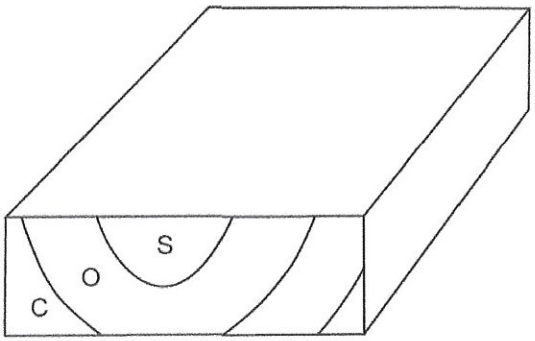




Directions

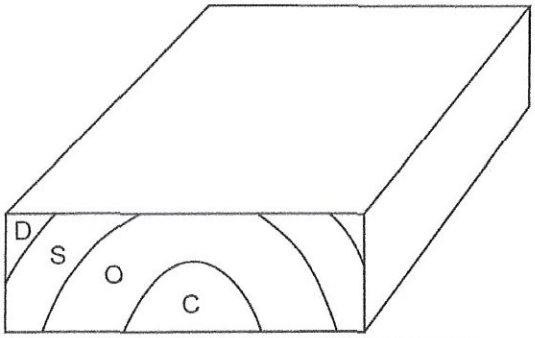
For questions 1-12 on the following two pages: (1) Answer questions on lines provided, (2) Complete any blank sides of the diagram by drawing in the geologic units/contacts, (3) Add 4 strike-dip symbols to each block diagram, and (4) Add appropriate map symbols. *NOTE*: You must consult a geologic time scale to determine the order of ages for units (C = Cambrian, O = Ordovician, S = Silurian, D = Devonian). Each diagram is 6 points (4 points for a complete drawing and 2 points for correct identification)

NAME: _____ Deformation



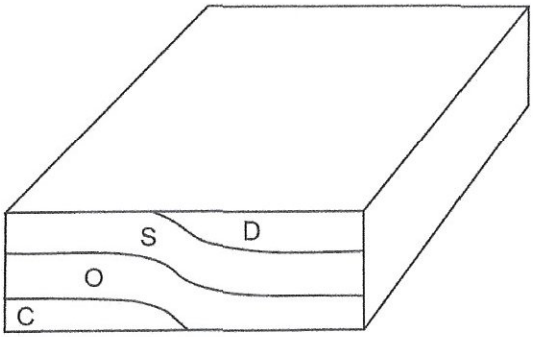
1) Add strike and dips symbols and a symbol that *defines the fold axis. What is the name of this structure?*

_____



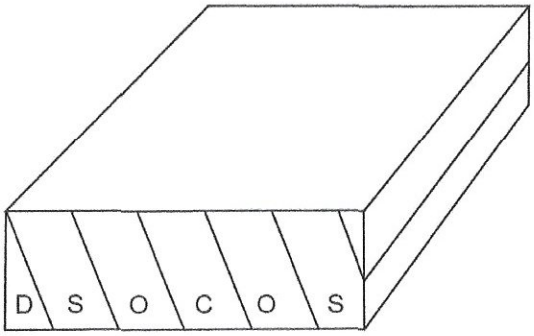
2) Add strike and dips symbols and a symbol that *defines the fold axis. What is the name of this structure?*

_____



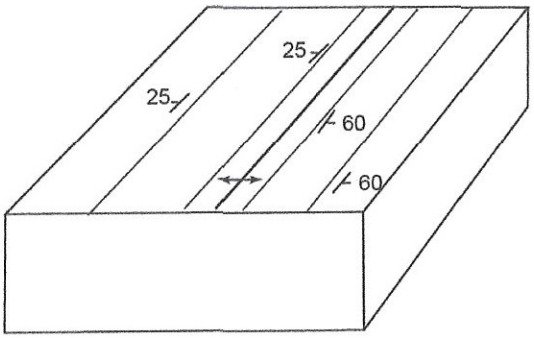
3) Add strike and dips symbols and a symbol that *defines the fold axis. What is the name of this structure?*

_____



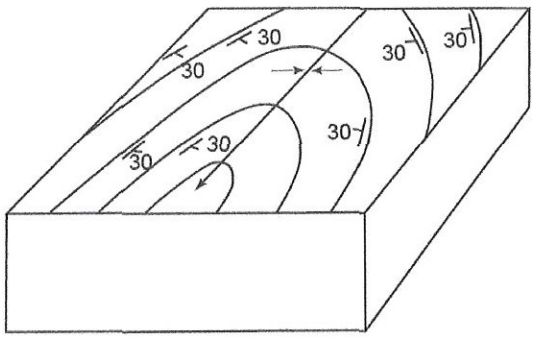
4) Add strike and dips symbols and a symbol that *defines the fold axis. What is the name of this structure?*

_____



5) What is the name of this structure?

_____

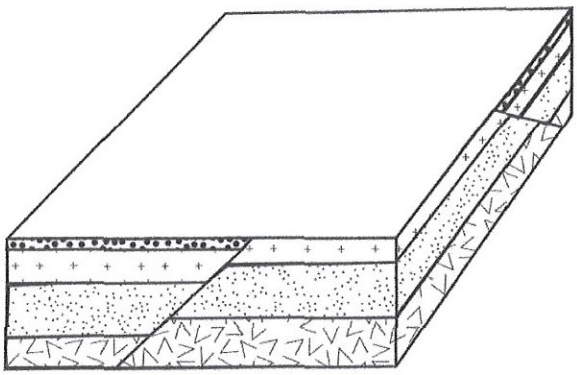


6) What is the name of this structure?

_____

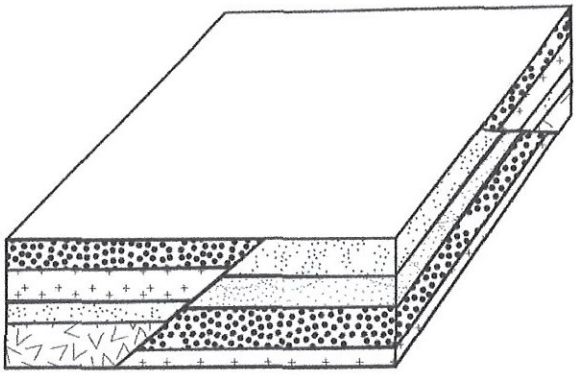
What is the difference between this structure and #1 structure? _____

_____



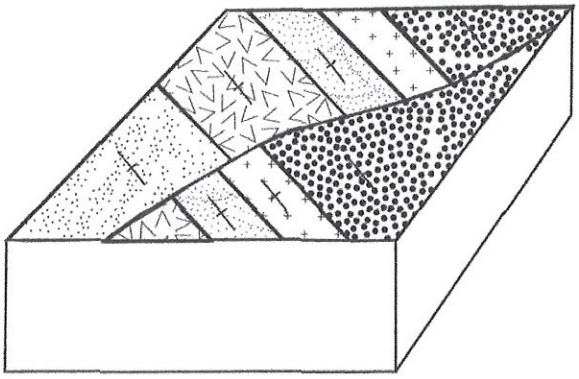
7) Add strike and dip symbols and symbols along the fault in cross section and map view.
What is the name of this structure?

_____



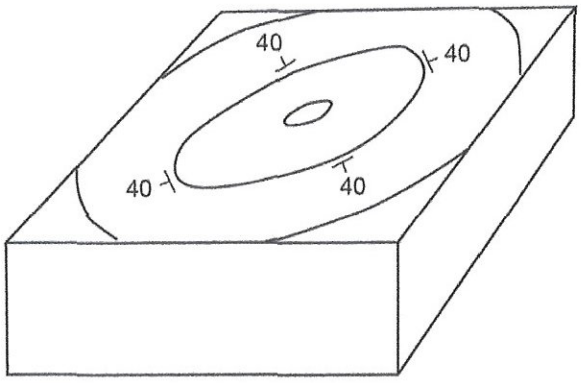
8) Add strike and dip symbols and symbols along the fault in cross section and map view.
What is the name of this structure?

_____



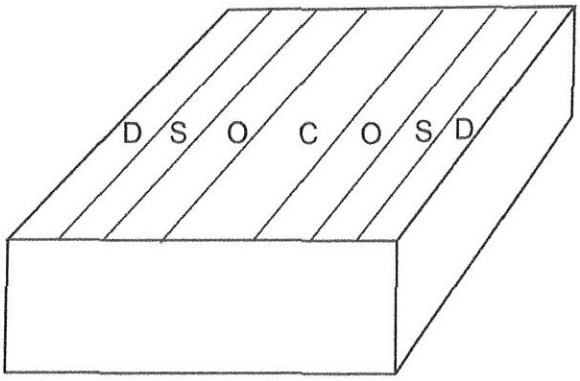
9) Add strike and dip symbols and symbols along the fault in cross section and map view.
What is the name of this structure?

_____



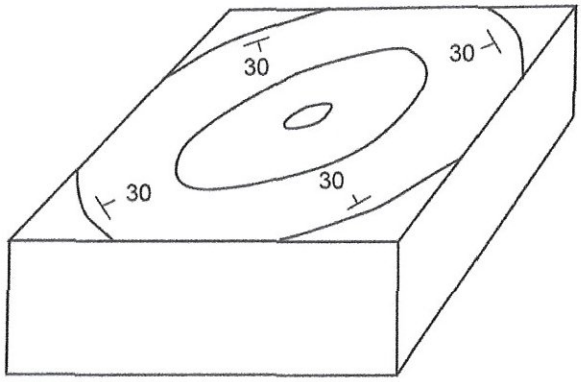
10) What is the name of this structure?

_____



11) Add strike and dips symbols and a symbol that defines the fold axis. What is the name of this structure?

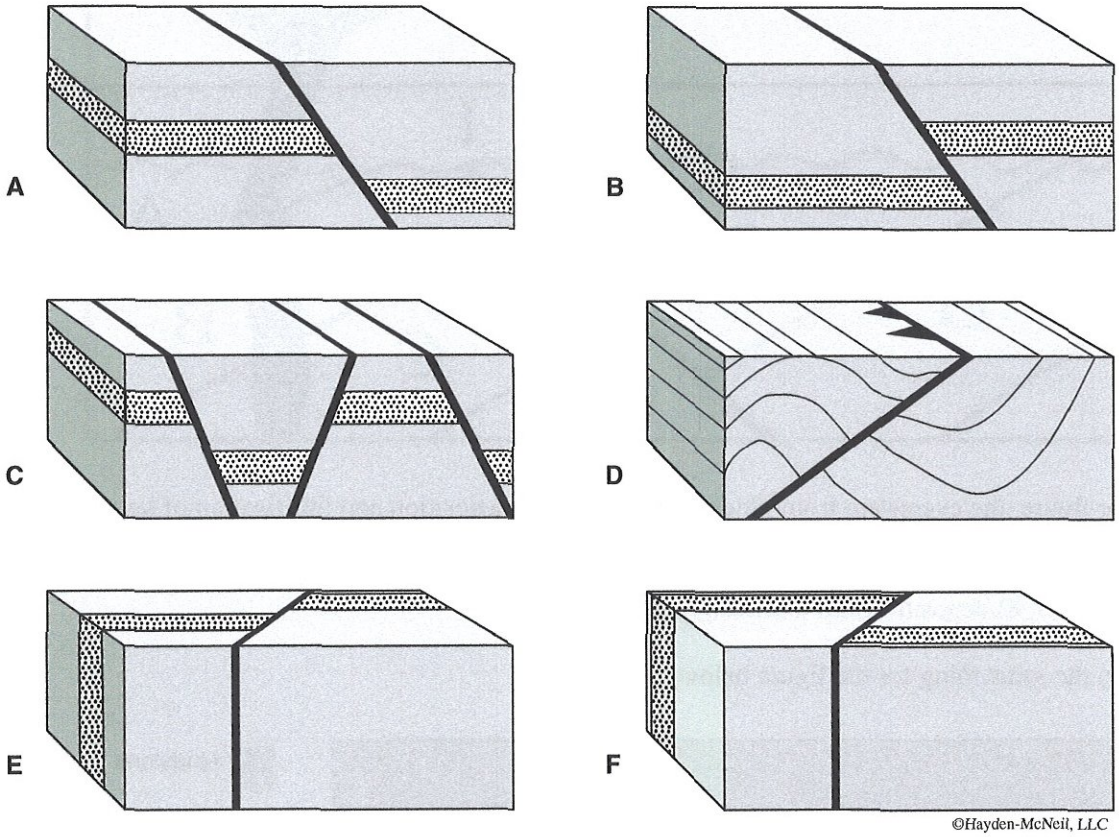
_____



12) What is the name of this structure?

_____

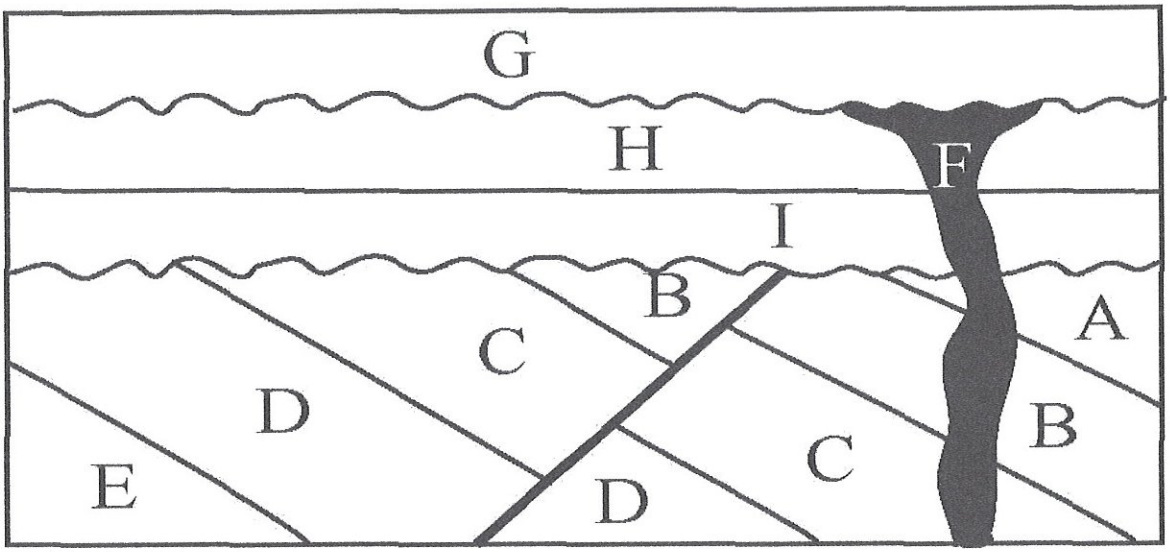
In the blanks listed below the figure, state what kind of fault each block represents, and then state the evidence for determining that. (12 points)



13. Please identify the fault types in the above figure.

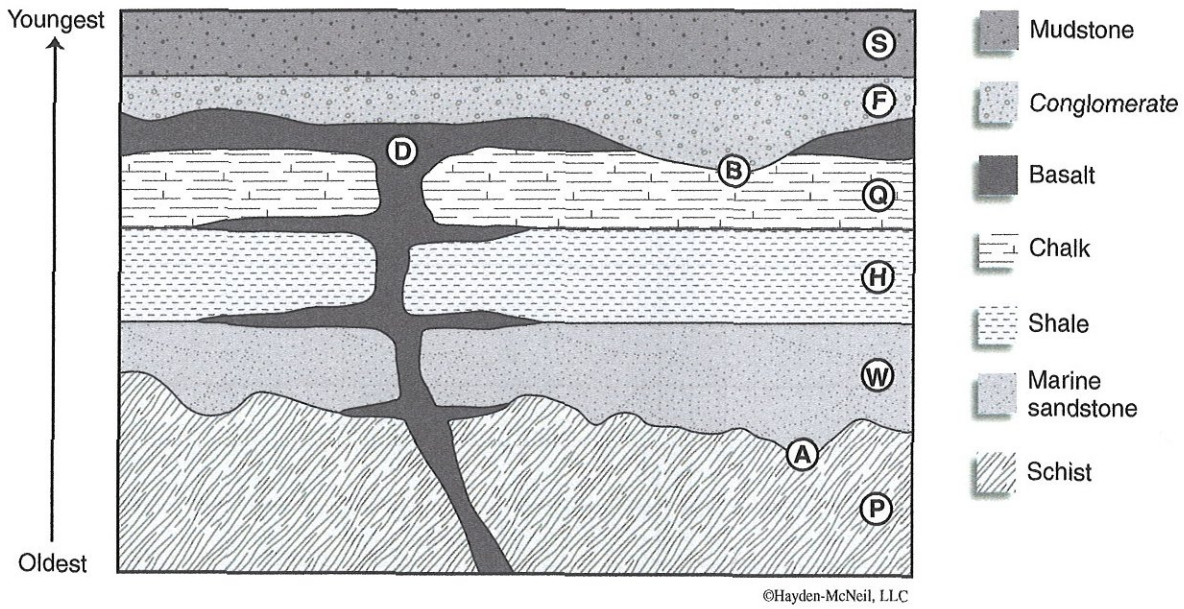
Letter	Fault types	Evidence
A		
B		
C		
D		
E		
F		

Relative Dating is a technique to determine a sequence of events without assigning an exact date. Look in your textbook to understand these principles if you have not covered them in your class yet: principle of uniformitarianism, principle of original horizontality, law of superposition, principle of cross-cutting relationships, principle of inclusions, and unconformities. Based on the principles, determine the geological history of the cross-section shown in Question 14. Concentrate on packages of events, instead of individual beds, e.g., "Deposition of V-Z" instead of "Deposition of V, Deposition of W, Deposition of Y, Deposition of Z". The first figure is a practice figure that your TA will walk you through.

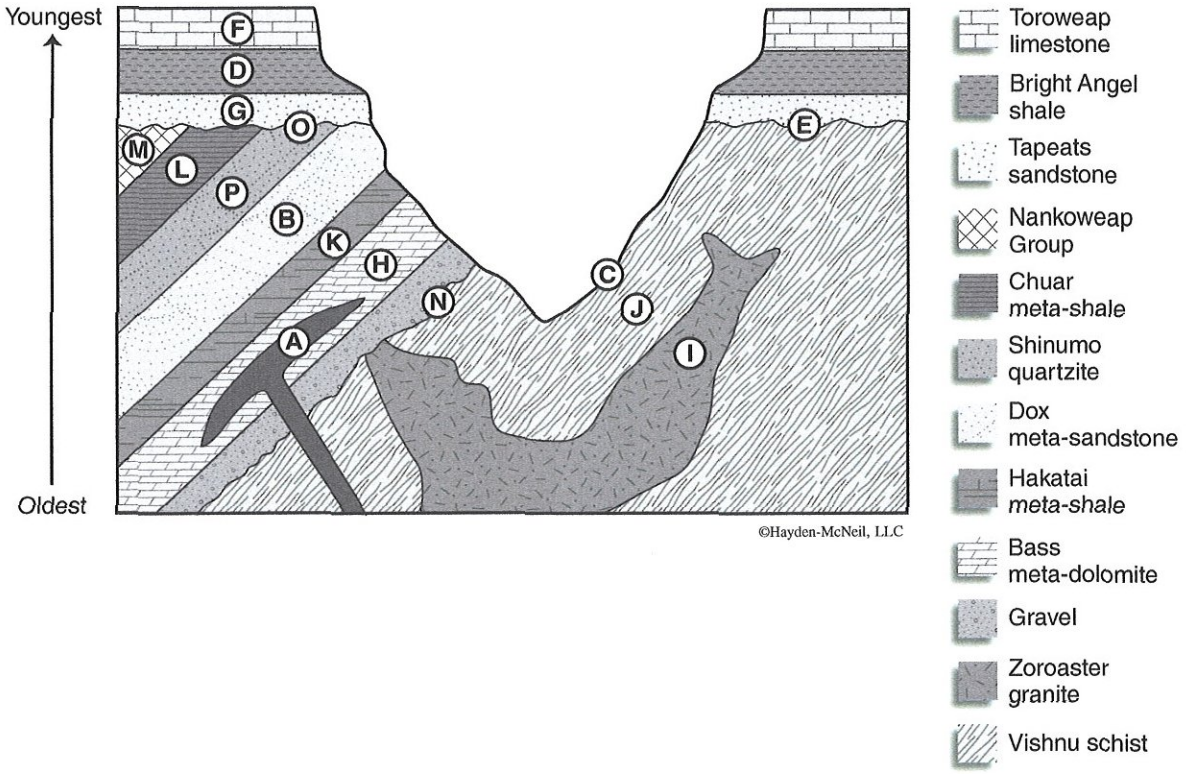


In the above figure, the events are from oldest to youngest: 1) deposition and lithification of layers E, D, C, B, A; 2) tilting of layers E, D, C, B, A; 3) faulting of layers E, D, C, B, A; 4) erosion (formation of angular unconformity); 5) deposition and lithification of I and H; 6) intrusion of F; 7) erosion (formation of disconformity); 8) deposition and lithification of G.

Now you do the same thing for the figure below.



14: List events from oldest to youngest.



15. Relative dating of the Grand Canyon. List events from oldest to youngest.

Chapter 12: Earthquakes and Faults

How do we know how materials in the Earth react to stress? We can't dig down 10 km and observe. Instead, we use analogue materials. In this laboratory, we will use Silly Putty as our analogue material to observe and hypothesize what happens along a fault.

LEARNING OBJECTIVES:

1) Understanding Force and Stress.
2) Converting between different measurement units and systems.
3) Understanding the role of shear, normal, and Coulomb stresses along a fault.
4) Simulating & calculating build-up, release, and relaxation of shear stress.

MATERIALS:

1 earthquake coupling device; 1 sheet of graph paper; calculator; protractor; ruler/straight-edge; clock/watch with seconds display; stiff brush

4 *oz. of silly putty* in a Ziploc bag – **PUT BAG IN YOUR POCKET ASAP/ DO NOT SIT ON IT**

Anyone involved to pilfer the silly putty will be referred to the Dean of Arts & Sciences for both Academic Misconduct and criminal theft investigations.

INTRODUCTION:

Earthquake sequences

Earth's rigid outer layer is divided into more than a dozen tectonic plates that are always in motion with respect to one another (see chapter 2). This relative motion causes stress to slowly build-up along plate boundaries, where the plates are frictionally locked together. When this stress eventually exceeds the frictional strength of the plate boundary (a *fault*) the plates instantaneously slip past one another (an *earthquake*) to relieve the stress.

In December of 2004, two of the Earth's plates catastrophically moved past each other near the Sunda Trench as a massive M9 earthquake released stress that had been building up for centuries. The movement triggered a tsunami that killed hundreds of thousands of people in Sumatra, Thailand, and India. In March of 2005 (three months later), an M8.7 earthquake ruptured a portion of the same plate boundary just to the southeast of the M9 earthquake. In 2007, a third earthquake (M8.4) ruptured the plate boundary to the southeast of the M8.7 earthquake (Figure 12-1a). Additionally, thousands of aftershocks (small earthquakes) saturate the near-field region of the M9 earthquake (Figure 12-1b). The proximity of these events in both space and time suggests that they are coupled, that is, stresses unleashed by the M9 earthquake triggered subsequent events.

How earthquakes are triggered

The device in this lab represents two plates moving with respect to one another (Figure 12-2). The sandpaper simulates the friction along the surface (a fault) separating the two plates. Turning the crank generates shear stress (stress that promotes sliding) caused by one plate, represented by the brick, as it tries to slide past the other plate, represented by the board. The spring, which represents the elastic rock surrounding the brick, allows the slow build-up of shear stress. As the crank is turned, shear stress along the fault (provided by stretching the spring) slowly builds up to a point at which the shear stress along the fault overcomes the normal stress (the stress that squeezes the brick and board together) scaled by friction. At that point the brick slips and releases the built-up shear stress – an earthquake! Plates are moving continuously so stress is building up continuously and then releases. The cycle will start again, building up stress. When the stress released, a fault moves. That movement of the fault causes energy to be released and sent through the rocks around the fault that is an earthquake.

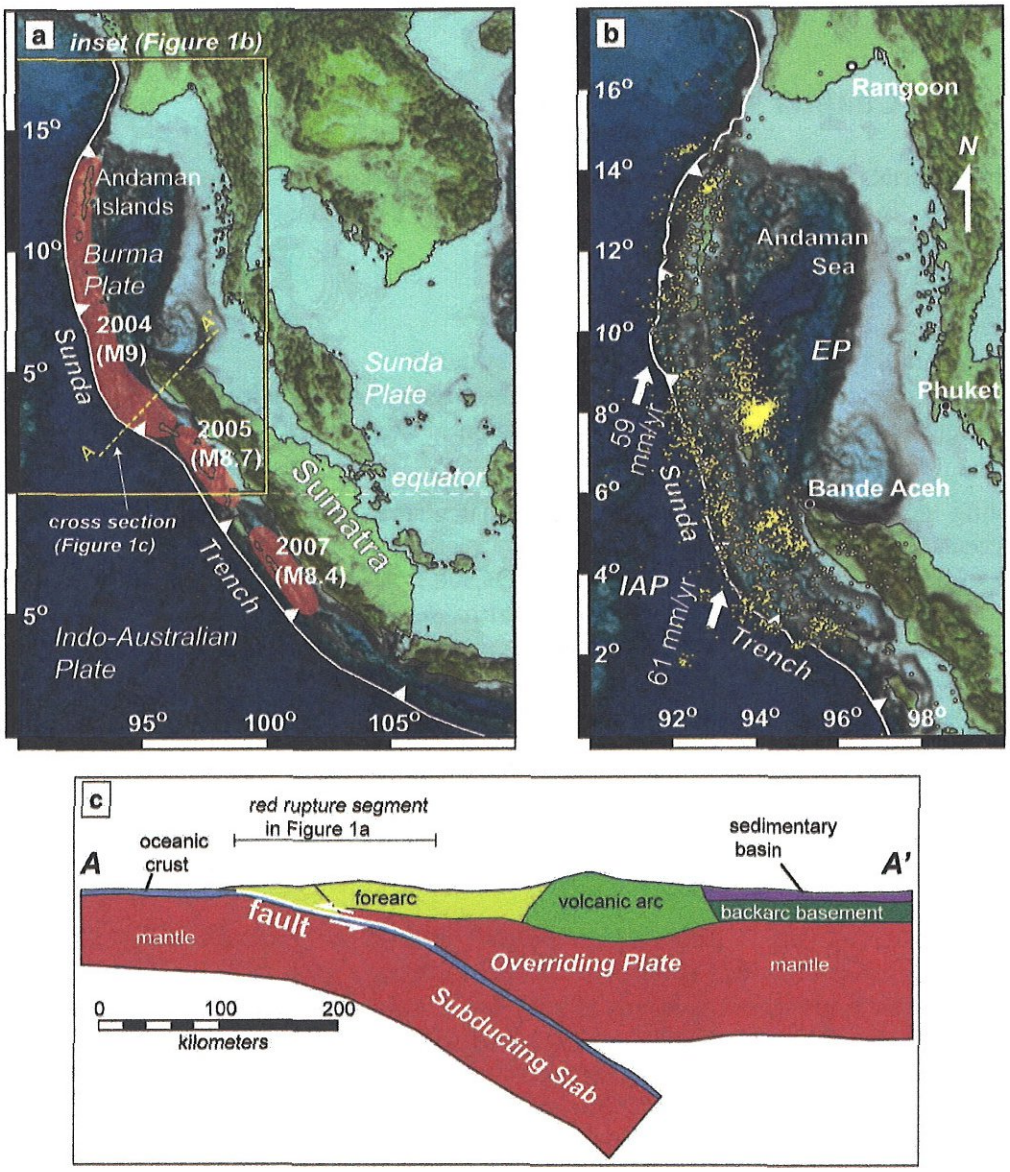


Figure 12-1. Earthquakes in a subduction zone. (a) Sumatra-Andaman Subduction zone. Ruptur segments (red regions) from recent earthquakes cover most of the plate boundary from th southern of Sumatra through the northern extent of the Andaman Islands. (b) Aftershocks (yellov dots) of the 2004 M9 Sumatra-Andaman earthquake. (c) Cross section of the plate boundary. Th M9 earthquake was caused by slip along the fault separating the subducting slab and overridin plate.

Force and Stress

Stress is Force/Area; Force = mass x acceleration (Newton's Second Law). The unit for Force is Newtons ($N = kgm/s^2$). The unit for stress is Pascals ($Pa=kg/ms^2$). If the mass of a brick is 1.13 kg. Using Newton's Second Law, calculate the force of the brick normal (perpendicular) to the sandpaper (Figure 12-2). Assume the acceleration of gravity is 10 m/s^2. Be sure to include the units in your answer.

(1) [3 points] _____ (mass) x _____ (acceleration) = _____ (Force)

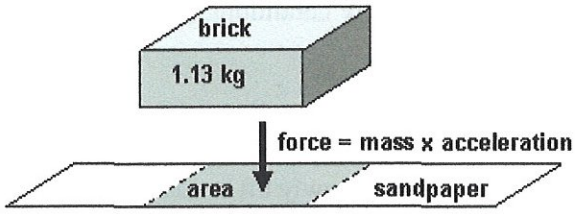


Figure 12-2

Use a yard stick to measure the dimensions for the face of the brick that comes in contact with the sandpaper. Express answers in centimeters & convert to meters. 1 meter = 100 cm.

(2) [3 points] Length: $\_\_\_\_\_\ \text{cm}\left(\frac{1\text{ m}}{100\text{ cm}}\right) = \_\_\_\_\_\ \text{m}$

(3) [3 points] Width: $\_\_\_\_\_\ \text{cm}\left(\frac{1\text{ m}}{100\text{ cm}}\right) = \_\_\_\_\_\ \text{m}$

Calculate the area of the face of the brick that comes in contact with the sandpaper. Express your answer in m^2.

(4) [3 points] _____ (length) x _____ (width) = _____ (Area)

Calculate the normal stress. Show your work and include the units. Express your answer in the SI units (*i.e.*, meters, kilograms, seconds, Newtons, Pascals, etc.). Normal stress = Force/Area. $Pa = N/m^2$

(5) [3 points]

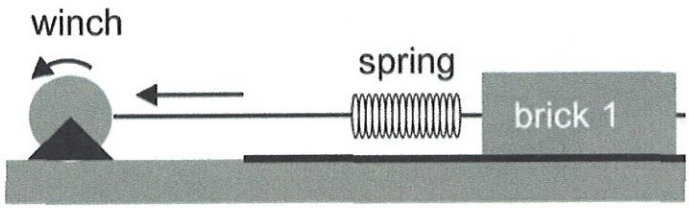


Figure 12-3. Earthquake coupling device.

Fault stability
Changes in the mechanical stability of a fault are quantified in terms of Coulomb stress.

$$\sigma_c = \sigma_s - f\sigma_n \qquad (1)$$

σ_c is Coulomb stress; σ_s is shear stress; σ_n is normal stress; f is the coefficient of friction.
If Coulomb stress increases (becomes more positive), a fault becomes less stable (tends toward slip). If Coulomb stress decreases (becomes less positive), then the fault becomes more stable (hard to slip). Otherwise, the fault is stable (will not slip). The fault stability is called critical if Coulomb stress = 0, then the slightest increase will trigger slip.

The coefficient of friction is estimated by simulating critical fault stability conditions ($\sigma_c = 0$), recasting equation (1) for critical conditions, and solving for f. The relationship is:

$$f = \tan\theta \qquad (2)$$

θ is the angle of inclination (Figure 12-4). Configure the device to simulate critical fault stability as shown in Figure 12-4. This requires a team of at least three people. **Person 1** will slowly lift one end of the device to increase the angle, θ. **Person 2** will (1) Keep the protractor aligned with the pivoting end of the board and (2) Observe and record the angle at which the brick slips as measured from the bottom of the board to the table. **Person 3** is responsible for safety –ensure the brick does not slide off the board. Repeat this process and fill in Table 12-1.

Table 12-1 [5 points] Objective: calculate Shear Stress (σ_s)

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	average
θ						
f						

Calculate the shear stress required to trigger slip for a brick that is not inclined and $\sigma_s = f\sigma_n$. Use the average f in Table 12-1. Use the normal stress calculated in (5). Show your work and express your answer in SI units.

(6) [5 points]

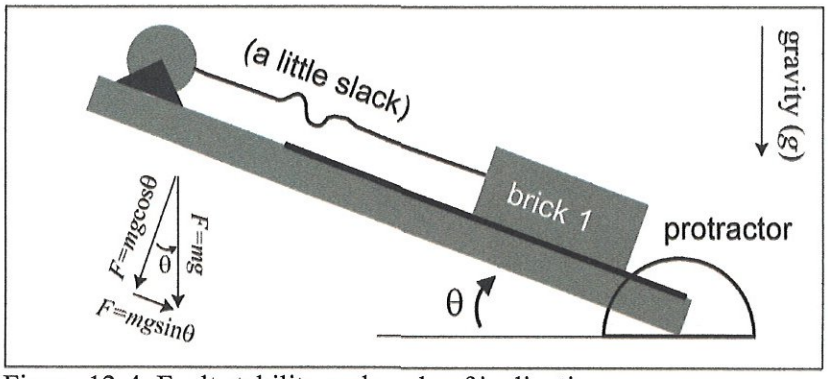


Figure 12-4. Fault stability and angle of inclination.

Objective: Calculate Spring Constant

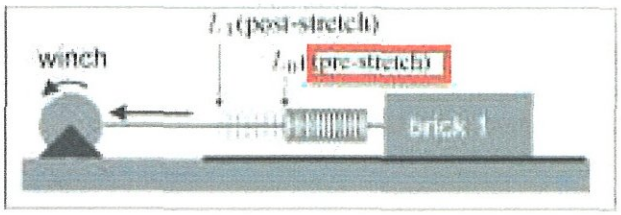


Figure 12-5. Spring Constant.

Brush the sandpaper to remove any loose sand. Place the brick with one eye-screw on the sandpaper as far as possible from the winch. Unwind the winch and hook the spring to the brick. With the ratchet on, slowly turn the crank until all the slack in the cable is taken up, but without stretching the spring. Record the location (Figure 12-5) of the end of the spring that is closest to the winch (L_0). Slowly turn the crank and record the position (L_1) of the end of the spring that is closest to the winch at the instant the brick begins to slide (at least 1 cm). Repeat this process and fill in Table 12-2. The relationship of the relative change in length of the spring the shear stress is:

$$\sigma_s = k\frac{(L_1 - L_0)}{A} \qquad (3)$$

where k is the spring constant and $(L_1 - L_0)$ is the relative change in length.

Remember, for this device, the spring represents the elastic rock surrounding the brick. For actual rocks, the spring constant is several orders of magnitude greater. Rocks can indeed be elastic, but are stiffer than the springs used here. Use principles of algebra to rearrange this equation in terms of k.

(7) [5 points] $k =$ _____

Trial	L_0	L_1	$(L_1 - L_0)$, m	k , N/m
1				
2				
3				
4				
5				
Average				

Table 12-2 [5 points]DO NOT FILL IN THE GRAYED OUT BOXES

Relaxing stress

While some faults are frictionally locked as tectonic stresses build-up, other faults 'creep' in response to shear stresses. Creep is slow slip (so slow that it does not release seismic waves) along a fault. You will now demonstrate how a creeping fault can relax accumulated shear stress. Brush the sandpaper to remove any loose sand. Remove the bag of silly putty from your pocket and take the silly putty out of the bag. Your body heat warms the silly putty, which is now the perfect viscosity (viscosity is temperature-dependent) for your purposes. Roll the silly putty into a cylinder that is a little longer than the brick. Place the silly putty on the sandpaper and place the brick on top of the silly putty, such that about one inch of silly putty sticks out in the winch direction. Push down on the brick to ensure that it is fixed to the silly putty (Figure 12-6).

Record the relaxed length of the spring in centimeters (L_0). Have one person hold the brick in this position, while another person attaches the spring to the brick and winds the winch such that the spring extends about seven inches longer than its relaxed length.

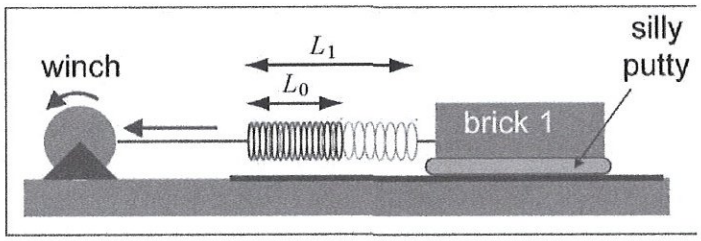


Figure 12-6. Relaxing stress with silly putty.

(8) [1 point] _____ (record the relaxed length of the spring)
(L_0)

Release the brick and record the position of L_1 in centimeters (Figure 12-6) every 20 seconds over a time interval of 4 minutes, or until the brick falls off the silly putty. Please do not stop it to read the value…read it continuously. Record these measurements on Table 12-3. Use equation (3) to calculate σ_s.

Table 12-3 (6 points)

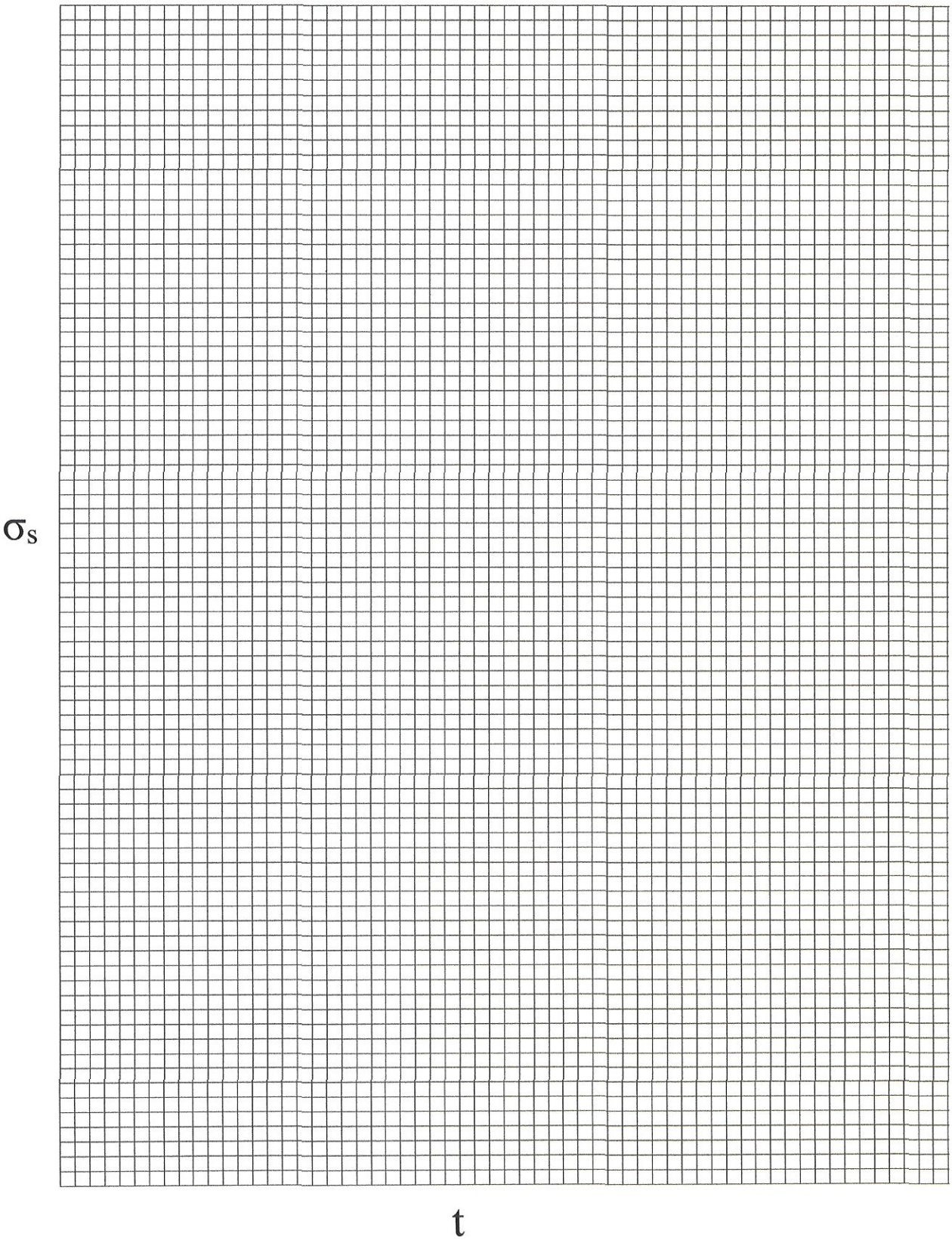
time, seconds	L_1	$(L_1 - L_0)$, m	σ_s, Pa	time, seconds	L_1	$(L_1 - L_0)$, m	σ_s, Pa
0				**120 (2 min.)**			
20				**140**			
40				**160**			
60 (1 min.)				**180 (3 min.)**			
80				**200**			
100				**220**			
				240 (4 min.)			

Plot your results on the graph paper on the next page. The horizontal axis will be time and the vertical axis will be σ_s. Ensure your plot includes a title, as well as axes labels and units. Draft your plot carefully and precisely (use the ruler for the axes). [6 points]

(9) Based on your plot, explain the behavior of σ_s as a function of time. [4 points]

(10) Did your graph show a decrease in σ_s with time? If so, explain why. If not, state why this is the case.

There are questions on the back of the graph paper.


σ_s
t

(11) On your silly putty, there are some features that were created when the brick and the board slid past each other. Examine your silly putty and draw these features in the space below.

(12) What would you suggest happened if you found these features in rock?

(13) In the real world, after a fault moves, σ_s decreases drastically just like you were supposed to find in this lab. What happens to σ_s in the time between when the fault moved (an earthquake) and the next earthquake?

Turn in all equipment (including silly putty) to your TA when you are finished.

Chapter 13: Seismology and Earthquake Location

How do we know the Earth is a layered body? How can earthquakes answer this question? Have you ever noticed that just minutes after the main shock of an earthquake is reported, that the epicenter (or location of the earthquake) and magnitude are already known? How is this done so quickly? In this lab you will learn how seismology indicates a layered earth and practice locating the epicenter of an earthquake.

LEARNING OBJECTIVES:

1) Understand the various phases of seismic waves.
2) Be able to identify seismic phases through the Earth.
3) Creating a travel-time plot from P- and S-wave arrival times.
4) Use real-world geophysical data to locate an earthquake within the U.S.

MATERIALS: ruler, **PENCIL**, compass, calculator

INTRODUCTION

Seismic Waves

A seismogram is a representation of the displacement (or direction of movement) of the Earth. Seismometers record displacements in three directions (or components): vertical (up and down), east-west, and north-south. Different seismic waves are better recorded on particular components of the seismometer based upon their direction of displacement. There are two types of seismic waves: **body waves** and **surface waves** (Figure 13-1). Body waves travel *through* the Earth, while surface waves travel across the surface of the Earth. The **body waves** within a seismogram are the P- and S-waves. The P-wave, or primary wave, is the first to arrive at the station (seismometer), while the S-wave, or secondary wave, is next. Due to their displacements, each wave travels at a different speed. The displacement of P-waves is in the direction of propagation (the direction the earthquake is traveling), and the displacement of S-waves is perpendicular to propagation. The P-wave displaces much like a Slinky does, and the S-wave displaces just like snake. The P-wave moves in a compressional motion. The S-wave moves in a shear motion. Shear displacement cannot occur within a liquid medium.

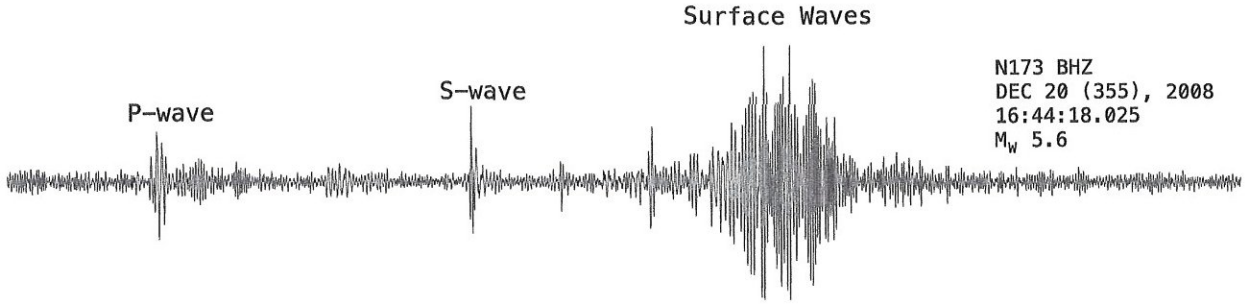


Figure 13-1: Seismogram depicting both **body waves** and **surface waves**.

The **surface waves** within a seismogram are the Love waves and Rayleigh waves. These are the very large amplitude waves that follow the S-wave arrival. Figure 13-1 shows the location of these large seismic waves. Love waves displace in the horizontal directions. Rayleigh waves displace in the vertical direction and have retrograde motion. Displacements for **body waves** and **surface waves** are shown in Figure 13-2. Surface waves travel at a much slower speed than body waves due to the free surface of the Earth that they travel along.

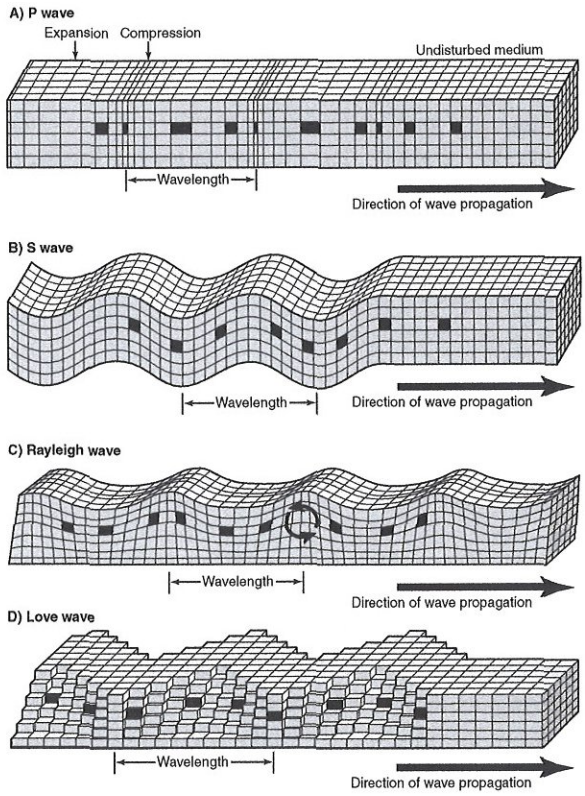


Figure 13-2: Figure showing the displacement directions with respect to propagation for the various seismic waves.

Seismic Waves Traveling Through the Earth

You've just learned the basics about **body waves** and **surface waves**. When ***body waves*** travel *through* the Earth, they bounce, reflect, bend, and essentially make their way all over the globe. Bending is caused by going from a fast medium (hard rock) to a slow medium (liquid) and vice versa. This bending of the waves is similar to what happens when you try to catch a fish in a lake. Because your hands are in the air and the fish is in water, the fish is not where you expect it to be. It is because the path taken by a ray of light crossing from air into the water is bent or refracted. The same thing happens when seismic waves travel through the Earth. They are bent as different materials are encountered (Figure 13-3). One earthquake creates all of these waves (P-, S-, surface waves), and they disperse in every direction from the epicenter (location of the earthquake). These different "bounces" and conversions can be identified, and by understanding these identifications, one can make some pretty cool conclusions about the subsurface of the earth. Figure 13-3 shows how many different bounces, bends, and reflections exist with just one earthquake. When seismic waves hit certain discontinuities (differing layers) they will convert from P- to S-waves depending on the material they are entering. Therefore, seismic waves can, and will, convert when they are meeting new media.

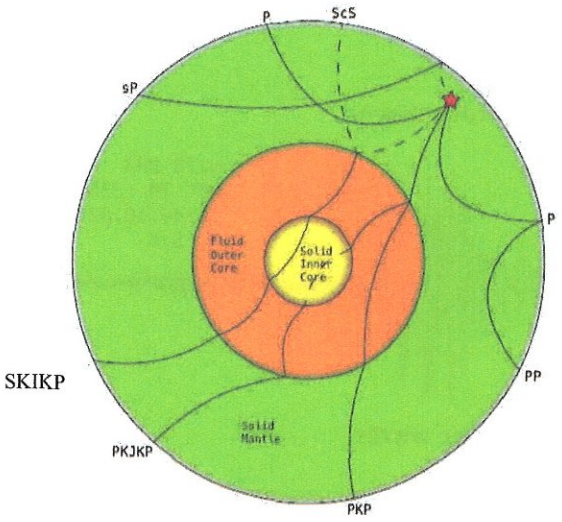


Figure 13-3: Figure showing the various bounces and bends of phases traveling through the earth from an earthquake (red star).

Travel-time Curves

Travel-time curves help us predict the arrival of various incoming seismic waves. This aids in many differing sub-disciplines of geophysics. The travel-time curve is an empirical (learned from actual scientific observation) curve that relates the arrival time of seismic waves to the distance the earthquake is away from the station. Figure 13-4 shows a typical travel-time curve and how to read it.

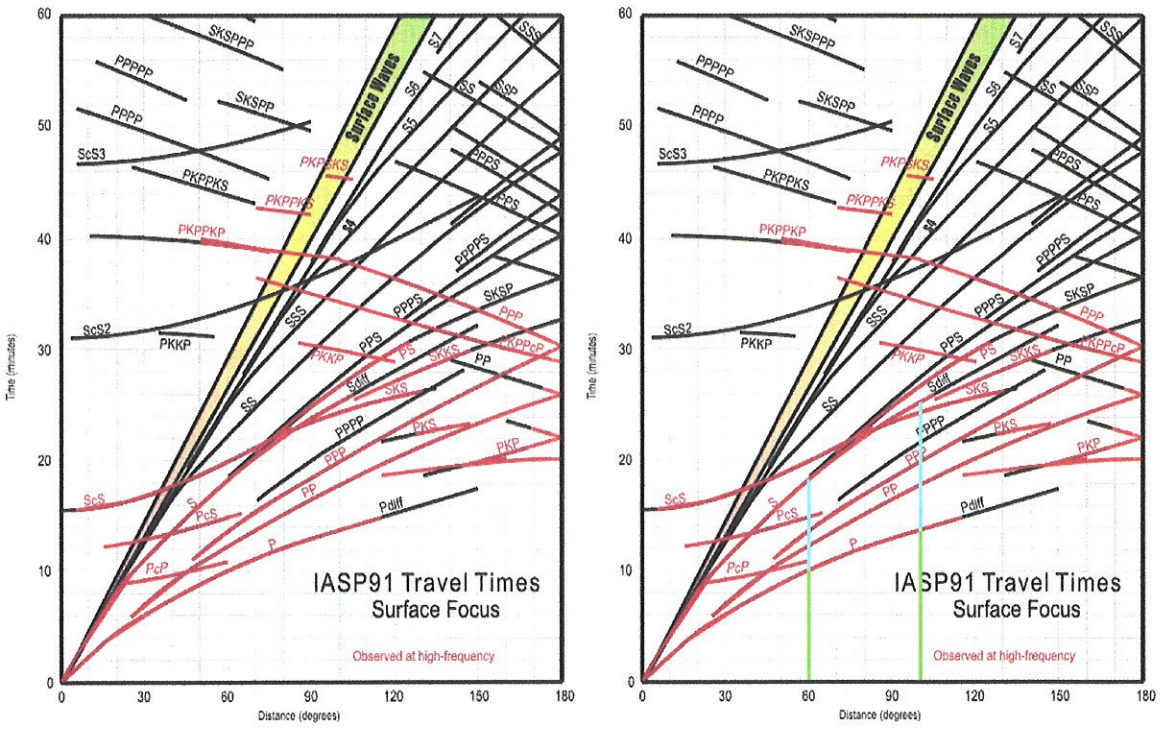


Figure 13-4: Travel-time curve from the USGS based upon the IASP91 global earth model. To the right, the blue and green lines show is how to read this travel-time curve. Times are read from the second the earthquake occurred. At 60° away, the P-wave arrival is expected at 10 minutes after the main shock (green line), and the S-wave is expected 18 minutes after the main shock (blue line). At 100° away, the P-wave arrival is expected at 14 minutes after the main shock (green line), and the S-wave is expected at ~25 minutes after the main shock (blue line).

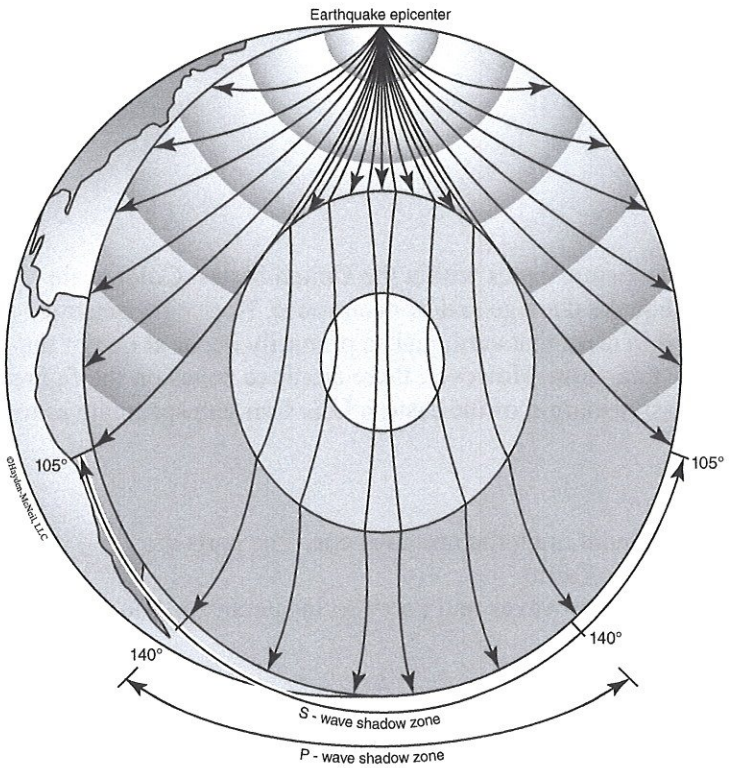


Figure 13-5: P and S wave shadow zones. At an earthquake epicenter, P- and S-waves travel through the Earth. At the outer core, S-waves will not travel through the outer core because it is molten. Thus, an S-wave shadow zone is produced on the other side of the earth, where S-wave will never reach between 105° and 105° from the epicenter.
P-waves will travel through the outer core but are refracted (bent). Because they are refracted, P-wave shadow zones are produced between 105° - 140° on each side of the earth from the epicenter.

Intracontinental Seismic Zones

Earthquakes located within the continent are, on average, quite small in magnitude, usually not affecting building structures or human safety. However, large earthquakes can, and do, occur within these areas. When these large earthquakes occur, damage is generally much worse within the continent than in the San Andreas fault system. This is because the rocks are much harder, colder, drier, and less fractured in the earth's crust in the central U.S. This leads earthquakes in these regions to shake and damage an area approximately 20 times more than earthquakes in California and most other active seismic areas. Figure 13-5 shows some of the most common seismic zones in the U.S. and their corresponding hazard analysis (how dangerous they are).

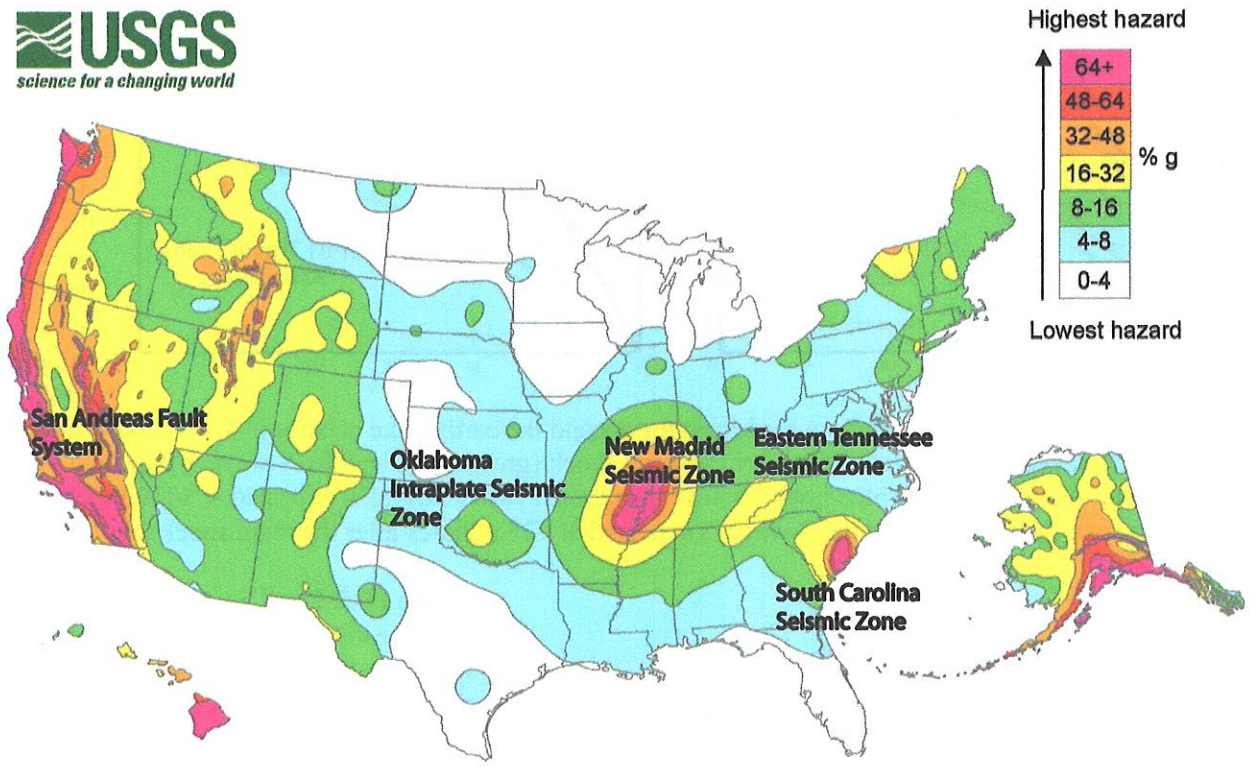


Figure 13-6: USGS Hazard map showing various seismic zones within the United States. Color scale indicates areas with the highest potential for earthquake damage and/or occurrence. Notice the seismic zones located *within* the continent. We've learned in class that earthquakes primarily occur at one of the three tectonic boundaries: divergent, convergent, transform. However, there are three zones on the figure above located within the continent and on the passive margin of the eastern U.S. Can you speculate as to how these zones could exist?

The Exercise:

This lab consists of two sections. Each section will build upon the previous one. The parts are:

1) Identification of seismic waves throughout the Earth.
2) Creating a simple travel-time plot with P- and S-waves and use it to locate an earthquake within the U.S.

Chapter 14: Coastal Processes

What makes a coastline look like it does? Why does Dauphin Island exist? What could make the island cease to exist in the near future? In this lab, we will explore these questions.

LEARNING OBJECTIVES:

1) Understand sea level variation over time.
2) Gain an understanding of how longshore drift affects landforms.
3) Exposure to extreme events.
4) Make observations concerning human adaptation to living at the coastline.

MATERIALS: Images in this chapter and your textbook.

INTRODUCTION:

Coastlines are dynamic areas affected by the constant interplay of waves, currents, tides, storms, sea level, and recently, human activity. As a consequence of these factors, rocks weather rapidly and sediments are perpetually moving in these regions. The position and geometry of any given coastline is therefore changing, even over short human timescales. This can create economic and social problems for those that live in or near the coast. The world's population is rapidly growing in coastal regions. Presently, coastal counties in the USA contain over 53% of the population, yet represent only 17% of total land area. With so much of the population focused in coastal regions, the economic and social impact of coastal sedimentary processes, especially erosion and sea level rise, continually increases (Figure 14-1).

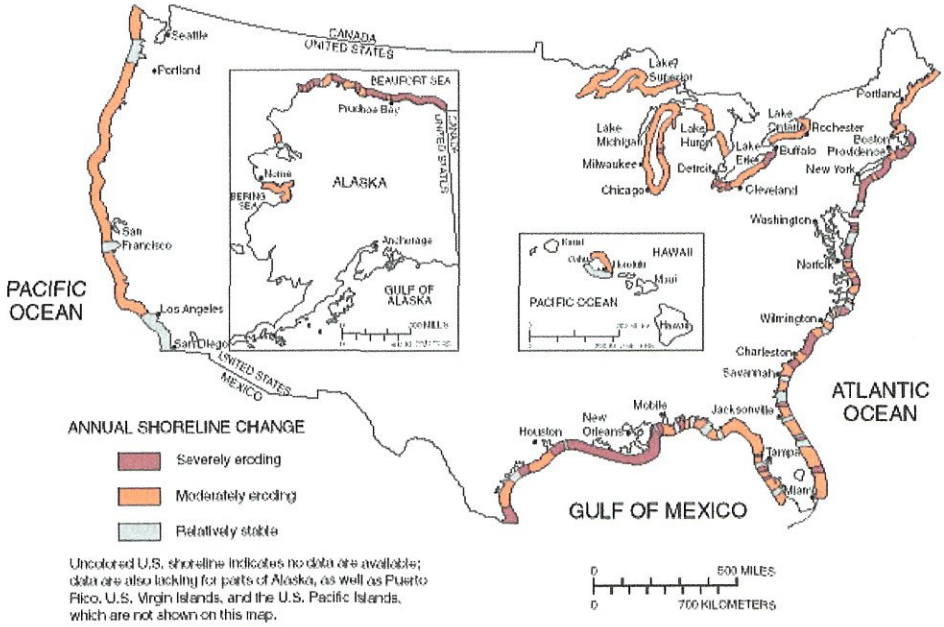


Figure 14-1: Erosion is a national concern. NOAA image.

In addition to these practical concerns, coasts are an important geological environment. Coasts are at base level for rivers, thus enormous amounts of sediment are deposited along the edge of continents. For this reason, many sedimentary rocks are derived from coastal environments of deposition. A geologist must understand coastal processes to understand the sedimentary rock record.

Alabama is a coastal state, and many aspects of coastal processes can be taught using local examples. This lab exercise will use photographs and data from Alabama to teach broader concepts that are applicable worldwide. However, it is important to note that each coast has unique characteristics that may cause these

processes to operate differently in other regions. For example, some coastlines are rocky, thus weathering and erosion processes would differ greatly from those coasts that are composed of loose sediment, such as Alabama. Also, tides in Alabama are very small and have less of an impact on coastal processes as compared to most other coasts of the world.

An additional reason, Alabama will serve as the central example in this exercise is the huge economic impact of coastal processes to all state residents. In addition to the tourists that visit our beaches every year, a great deal of Alabama's commerce and trade depends on shipping between our coast and the rest of the world. As we will see, coastal processes directly impact these activities. For example, Alabama spends millions of dollars replacing sand lost to erosion on beaches. Even more money has been spent to constantly dredge our shipping channels.

To understand how coastlines change, one must understand the primary agent of that change - water. Sea level dictates the point at which currents and waves will impact the continents. The surface currents and waves in the ocean are controlled by winds. The winds that drive most current and wave formation are relatively constant and are called "trade winds." As a result, water movement in a region follows generally stable patterns during periods of typical climate. These patterns can be disrupted by extreme events such as hurricanes. Each of these issues will be explored in this lab exercise.

Sea Level

The height of the surface of the ocean relative to land (**sea level**) varies through time. Sea level variation can be global (**eustatic**), caused by the advance and retreat of large continental ice sheets, or it can be local, possibly caused by **subsidence**, sediment accumulation, or tectonic uplift. As sea level rises or falls, locally or globally, stream **base level** changes with it, therefore patterns of erosion and deposition are altered accordingly. Also, sea level dictates where waves and currents will impact a coastline and thus control sediment redistribution. Sea level is currently rising, and this is expected to continue.

Longshore drift

Waves are caused and driven by wind. Coastal areas are subject to constant winds, called **trade winds**, which cause waves to approach the coastline from generally the same direction over time. In most places, wind and waves approach the coastline at an angle. Although the bending of waves, **wave refraction,** will cause the waves to become more and more parallel to the shoreface as they approach the coast, waves usually at an angle when they break. After the wave breaks, the water will be pulled by gravity back towards the ocean in a line roughly perpendicular to the shoreface. This results in a zig-zag pattern of water and sediment movement (Figure 14-2A). The net direction of this movement will be along the beach in one direction or another and is called longshore drift (Figure 14-2A). The current that moves the sediment is the **longshore current** and is responsible for a great deal of daily change in coastal landforms.

Because of longshore drift any given stretch of coast is likely either gaining (**accreting**), or losing (**eroding**) sediment. Even coastal areas that do not seem to be expanding or shrinking are likely in a state of dynamic equilibrium where sediment is being lost and gained at similar rates. As sediment moves along a coast due to longshore drift, it may create longitudinal accumulations of sand (**sandbars**), sometimes partially or entirely across the mouths of bays and inlets. A **spit** partially blocks a bay mouth, while a **baymouth bar** blocks it entirely (Figure 14-2B). Should a section of a spit or baymouth bar break off from the larger sandbar, it may become a **barrier island**. Barrier islands may also form through accumulation of sand through wave action, or rising sea level may inundate low lying land surrounding a rise.

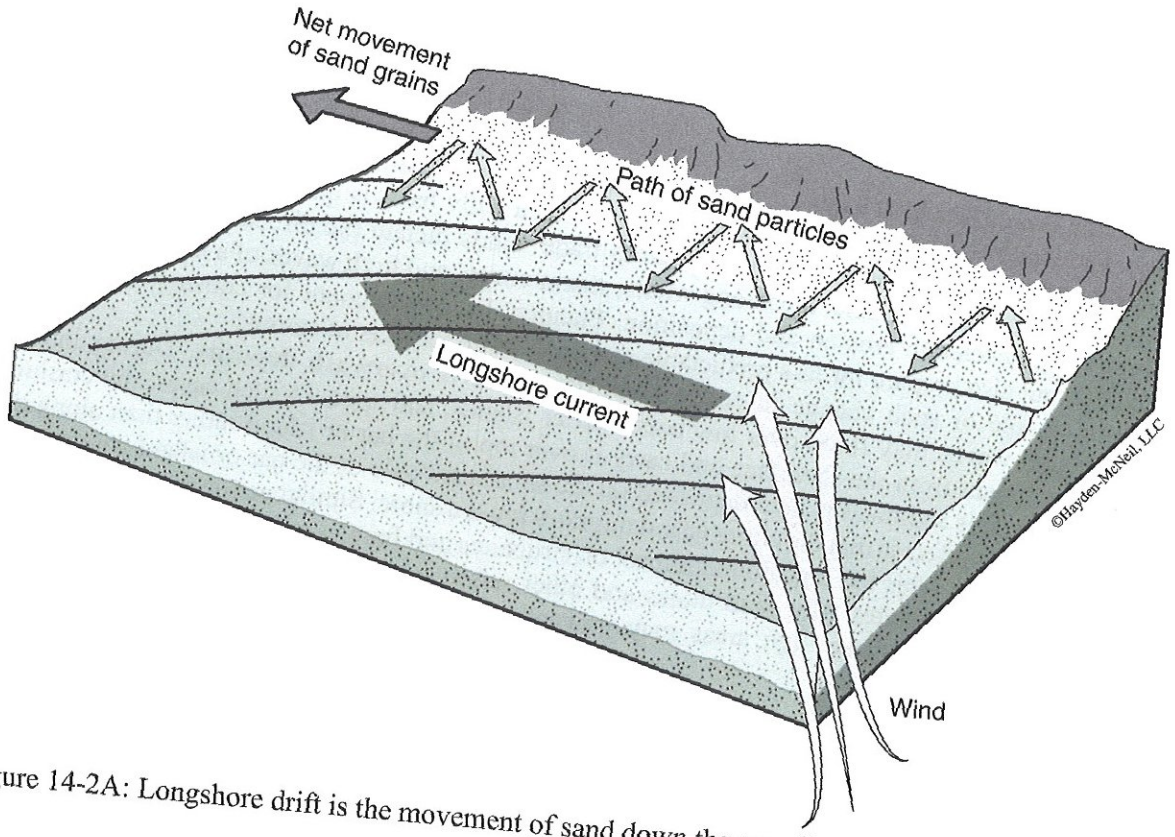


Figure 14-2A: Longshore drift is the movement of sand down the coastline due to the longshore current.

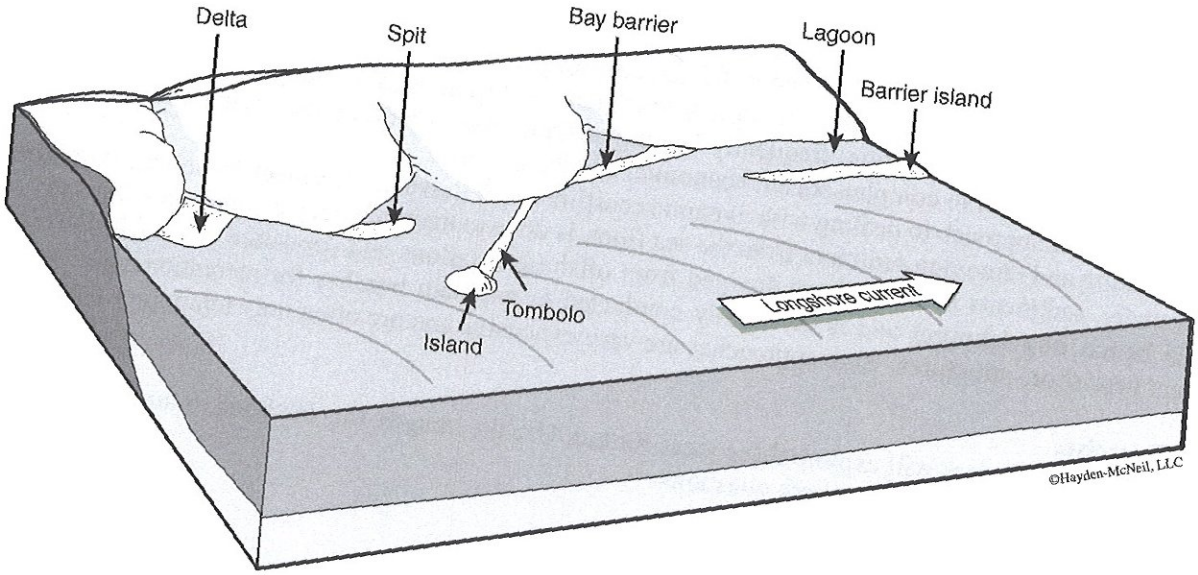


Figure 14-2B: Formation of a spit, baymouth bar and barrier idland due to transport of sediment in the longshore current by longshore drift.

Extreme events

Extreme events like **hurricanes** often change the coast in a very different fashion than what occurs day-to-day. The way in which we adapt to coastal change on a daily basis is quite different from what is needed during more catastrophic conditions. Whereas trade winds dictate the direction and intensity of waves and currents most of the time, the strong winds, **storm surge**, and high waves of a hurricane change these patterns and accelerate erosion and deposition. Planners have to account for constant factors like longshore drift, but also prepare for less predictable and more rapid impacts of storms.

One example of such change in erosion and deposition is **overwash deposits**. During intense storms, surges and waves may flood over low bars, barrier islands, and spits. In such cases, the crashing waves entrain sediment from the shoreface and carry it over top of the bar or island rather than along the shore as is typical. This sediment is then deposited on the shoreward side of the bar or island where wave energy decreases. The effect is that the entire island migrates toward shore. Similar action takes place during periods of sea level rise. This has a profound impact on structures and human activity on the moving land. This process also demonstrates why sand dunes and other raised topography serves as protection from hurricane damage because these high areas may prevent overwash. Plants also serve to stabilize the sediment.

***Human adaptation*:**

Since coastal regions are so economically significant a great deal of money and effort are spent toward keeping them suitable for our uses. This often means attempting to stop natural coastal processes or alter them to our advantage. Much of these adaptations are through engineering. **Riprap** (rocks dumped on the shore face) and **seawalls** built along the coast are meant to stop or slow down erosion and possibly encourage deposition. Another common structure are **groins**, which are lines of rock set perpendicular to shore to trap sediments moving with longshore drift. Similar structures called **jetties** extend out from the mouths of rivers, bays, and inlets to maintain deep shipping channels. As we will see these structures often fail to achieve their intended purpose and in fact create new problems. One common consequence of these structures is that they cut off or alter the normal longshore drift in an area, causing significant changes to patterns in erosion and deposition, frequently leading to rapid loss of land in one region and accretion in another. This may lead to complex social, economic, and legal issues.

Another approach to dealing with dynamic coastlines is to move the sediment ourselves. **Dredging**, or excavating and removing sediment from the sea floor, is done to maintain deep channels for ships to use. Conversely, sediments are sometimes dredged from offshore locations and deposited on beaches. This is called **beach nourishment** and is commonly conducted to maintain beaches for recreational use and to protect near-shore structures. Both approaches are very expensive and are often only temporary remedies.

The Exercise:

The following exercises will explore these ideas further. Use the images, this lab book, your class text, and logic and observation to answer these questions.

Natural Features:

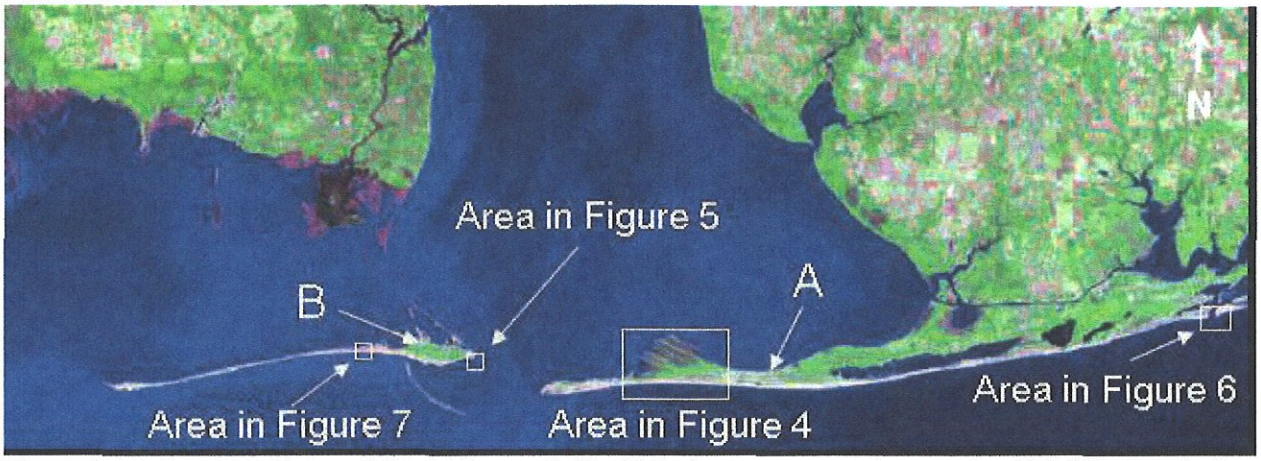


Figure 14-3: Landsat photo of the Alabama Gulf of Mexico coast near the mouth of Mobile Bay before Hurricanes Ivan and Katrina. The green areas represent land covered in vegetation. Refer to this figure throughout the exercise to define the spatial relationships of the areas depicted in later figures (white boxes). In the picture, Figure 4 is Figure 14-4 in the lab manual; Figure 5 is Figure 14-5 in the lab manual; Figure 6 is Figure 14-6 in the lab manual; Figure 7 is Figure 14-7 in the lab manual. Adapted from NASA.

Answer the following based on Figure 14-3:

1) What type of feature is Fort Morgan Peninsula (A)? (2 points)

2) What type of feature is Dauphin Island (B)? (2 points)

3) What direction is most longshore drift here? (2 points)

4) How can you tell the direction of the most longshore drift? (2 points)

5) Where does the sediment that forms Dauphin Island (B) come from? (2 points)

6) What do you think the consequences of frequent dredging of the ship channel are to Dauphin Island? (note – this is an ongoing and expensive legal issue for the state of Alabama)? (4 points)

Figure 14-4: Fort Morgan Peninsula. Location is Figure 4 on Figure 14-3. Image modified from Google Earth/NASA satellite photo.

Answer the following based on Figure 14-4:
7) The features pointed out by the arrows are sandy ridges. How do you think they formed? (2 points)?

8) Do you think Fort Morgan Peninsula is currently growing to the west? (Think about question 6 in your answer)? (2 points)

9) If the mouth of Mobile Bay was entirely blocked by a sandbar, what would it be called? (2 points)

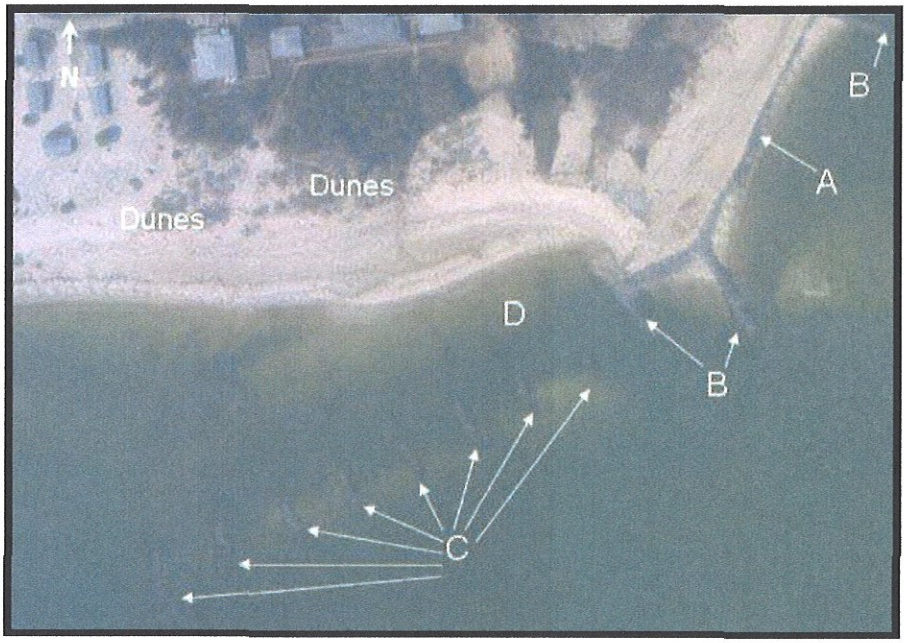


Figure 14-5: East end of Dauphin Island, August 2005, NOAA photo. See Figure 14-3 (location of Figure 5) for context within the overall Alabama coast. (Adapted from NOAA)

Answer the following based on Figure 14-6:
10) What are the two artificially constructed lines of rocks (A) called? (2 points)

11) What are the straight lines of rocks and concrete (B) called? (2 points)

12) What impact do you think the structures labeled "A" have on the beach on the west side of the pass? (2 points)

13) Which area on Figure 14-6 would be the safest to build resorts and where would be the most likely to erode away? (2 points)

Figure 14-6: Perdido Pass near the Alabama-Florida border. Image modified from Google Earth satellite photo. See Figure 14-3 (location for Figure 6) for context.

Extreme events:

Figure 14-7: Time-series aerial photographs of Dauphin Island facing north from the Gulf of Mexico. A: After Hurricane Ivan, but before Katrina (2005) B: After Katrina (2005). Arrows point out houses for reference. Note the low topography of the land and lack of dunes. See Figure 14-3 (location for Figure 7) for context. (Adapted from USGS)

Answer the following questions based on Figure 14-7 above:

14) What direction is sand moving during these hurricanes? (2 points)

15) If this continues with future hurricanes, what will happen to the island? (2 points)

16) Sea level is currently rising globally. How do you think the island will respond to this? (4 points)

The following are questions about Dauphin Island. Look at Figure 14-3 for a bigger view of the island. It is the only island on the figure.

17) If there were no hurricanes, which location would be the safest to build a house where it is protected from erosion—the eastern or western part of the island, why? (4 points)

18) Is the east or the west part of the island more protected from hurricane overwash and why? (4 points)

19) Considering all the regions in Figure 14-3 along our coast, which area seems least likely to erode through longshore drift and why? (4 points)

20) Evaluate the coast of Alabama's overall response to coastal processes. (10 points)

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